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Multipath Runway Exits and Taxiways

January 1993

Final Report

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U.S. Department of Transportation
Federal Aviation Administration

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1. Report No. DOT/FAA/CT-92/19	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MULTIPATH RUNWAY EXITS AND TAXIWAYS		5. Report Date January 1993
		6. Performing Organization Code
7. Author's) Everett S. Joline*		8. Performing Organization Report No.
9. Performing Organization Name and Address *Aviation Simulations International, Inc., Huntington, NY for MiTech Incorporated Atlantic City, NJ		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DT FA03-90-C-00036
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code ACD-110

15. Supplementary Notes
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Technical and contractual assistance to COTR provided by
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16. Abstract

As the level of air traffic demand increases in the future, and as advances are made in air traffic control technology to accommodate this traffic, the congestion resulting from aircraft moving on the ground may well become the limiting factor in airport capacity.

A family of multipath concepts, based on the use of parallel redundancy for the key components of the airfield system, has been proposed as a means of ameliorating these problems. With these concepts, the number of runway crossings, departure queues, runway exits, and taxiways to/from gates would be increased relative to the design practices of today.

An airport simulation model is used in this study to demonstrate each of the proposed concepts, as applied to six existing U.S. airports, and to develop quantitative estimates of the benefits of reducing delay and increasing throughput.

The results show that while significant improvements in performance can be obtained, the application of a particular concept to a particular airport depends heavily on the characteristics of that airport. The study also demonstrates how simulation can be used as an effective tool for evaluating airport improvement alternatives at a specific airport.

17. Key Words Airport Configurations The Airport Machine Simulation Model	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 106	22. Price

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1. Introduction

This report on the study of multipath runway exits and taxiways has been written by Aviation Simulations International, Inc., of Huntington N.Y., in fulfillment of a subcontract from the MiTech Corporation under FAA contract DTFA03-90-C-00036.

1.1 Background and Objectives

Due to the steadily increasing demand for air transportation, and considering the many constraints on increasing airport capacity to match this demand, increased attention is being given both to optimization of existing airport facilities and the optimum design of future new facilities.

This interest in the improvement of airport design is also motivated by evolutionary changes that have taken place in the way airlines operate their fleets. For instance, the introduction of hubbing operations at many of our busiest airports has complicated airport operations by concentrating airside activity in shorter periods of time, making operations quite sensitive to the timing of the arrival and departure rushes. Improvements in air traffic control technology are permitting reduction of the minimum separations required, thus increasing the stress on the airport to accommodate this demand.

Also, airport designers are becoming aware that it is not sufficient to plan only for the normal or average-day circumstances. Off-design conditions, that seem to occur so much of the time in the real world, must also be considered. For instance, the handling of early arrivals that have no gate positions, and departures that are holding for ATC clearance without interfering with other airport traffic can be a severe problem at many airports.

It is necessary therefore to rethink some of the standard design practices and standards that have been used in the past.

One family of concepts that has been proposed to ameliorate these problems is that of parallel redundancy for certain of the critical airport components. This redundancy is intended to enhance the flexibility of airport operations so that a smooth and efficient airside operation can be maintained in spite of wide variations in demand patterns, weather, and parameters of the ATC environment.

However, because the geometry, demand patterns, and other circumstances of existing airports vary so extensively, it is quite difficult to evaluate the potential benefits of these proposed concepts, or even to visualize their operation.

The subject study therefore has been conceived to evaluate the potential of parallel redundancy concepts by embodying them in existing or planned airports and then evaluating the performance improvement using computer simulation. The operation of the airport with and without the modifications in place can be graphically displayed in animated form to aid in visualization. Detailed statistical results are provided to quantify the value of the benefits thus displayed.

The primary model used in the study is The Airport Machine simulation model. This model (described in Appendix A) is unique in that the movement of flights can be viewed on a graphics screen as the simulation progresses and the user can interact with the model using a mouse to reroute flights, assign runways and perform other functions to resolve special problems that may arise due to high airside congestion levels.

1.2 General Approach

The Statement of Work for the study of multipath runway exits and taxiways describes three tasks to be performed. Each task addresses a particular subset of the concepts that are to be evaluated under that task.

The simulation experiments that were to be conducted under the various tasks were performed using six representative airport configurations. These six baseline configurations were selected from a group of 12 U.S. airports that have previously been simulated by ASI. The configurations used to perform the simulation experiments are described in section 2.

The simulation runs on the baseline configurations were performed under task 1. These baseline statistics were used in subsequent experiments to evaluate the benefits of the various concepts.

Task 1 also evaluated the multiple departure queuing and multiple runway crossing concepts.

Task 2 evaluated multipath runway exits and sensitivity to fleet mix variations.

Task 3 evaluated the benefits of multiple taxiways between gate groups and the runway, and investigates the impact of taxiway geometry design parameters.

Table 1 shows the airports that were used to analyze each concept.

Table 1.1

Assignment of Subtasks to Airports

		PHL	SEA	IAD	DFW	DIA	JFK
	Baseline Configuration	X	X	X	X	X	X
Task 1	Multiple Runway Crossings	X	X				
	Multiple Departure Queues			X	X		
Task 2	Multipath Runway Exits	X	X	X	X	X	X
	Fleet Mix Variations	X		X			
	Multipath Taxiways to and from Gates	X		X			
Task 3	Gate Groups	X		X			
	Taxiway Geometry Design	X					

Sections 2 through 7 of the report provide a description of the simulation experiments performed to analyze each parallel redundancy concept and the results obtained.

Before investigating the value of a proposed concept in the context of an actual airport, it was found desirable to investigate the basic objectives of the concepts and the general effect of the parameters of the concepts on their performance. These sections will therefore discuss some of the generic properties of the concepts so as to explain how the concepts were applied in subsequent simulation experiments.

The input data and statistical reports generated by The Airport Machine for all experiments performed are summarized in Appendix B and are supplied on disk.

1.3 Design of Experiments

Three measures of airport performance were used to evaluate the benefits of the proposed parallel redundancy concepts:

- runway throughput

- runway delay

- taxi time and delay.

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The most appropriate measure of performance for a particular set of experiments depends on the objectives of the evaluation being performed. Table 1.2 summarizes the performance criterion used to evaluate each of the concepts studied.

Table 1.2

Evaluation Criterion Assignments

	Runway Throughput	Runway Delay	Taxi Time and Delay
Multiple Runway Crossings		X	X
Multiple Departure Queues		X	
Multipath Runway Exits	X	X	
Fleet Mix Variations	X		
Multipath Taxiways to and from Gates		X	X
Gate Groups		X	X
Taxiway Geometry Design		X	X

The experimental procedures for evaluating runway throughput are somewhat different from those for evaluating delay since, by definition, the evaluation of runway throughput requires that there always be a flight available to land or take off. For these experiments, artificial techniques such as holding all arrivals or departures were used to accumulate the necessary backlog so that the full-queue assumption would be valid for a sufficiently long interval.

The evaluation of delay, on the other hand, requires that the flow rates and diurnal distribution of demand be representative of the actual flow rates expected at the airport.

For the evaluation of multipath runway exits it was desirable to assume that arrival/arrival separations are reduced in the future so that runway occupancy becomes the limiting factor controlling arrival acceptance rate. The arrival separations were therefore experimentally reduced until further reduction would cause an unacceptable number of runway incursions.

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2. Baseline Configurations

This section describes the airport configurations that were simulated to evaluate the proposed parallel redundancy concepts. All six baseline configurations were obtained by updating previously used Airport Machine simulation data to take advantage of the latest program updates. Diagrams of the subject airports showing the experimental enhancements, assumed taxi flow directions, and runway use are supplied in Appendix C.

2.1 Philadelphia International Airport (PHL)

PHL, operating in VMC with west-south flow, was used for experiments involving multiple runway crossings and multipath runway exits. Arrivals were divided between runways 17 and 27R while departure operations were conducted exclusively on runway 27L. During runway crossing experiments, runway 17 was used primarily for commuter and general aviation arrivals. This runway was not used in experiments involving testing of throughput improvements due to multipath exits. For these experiments all arrivals were placed on 27R so as to ensure a representative mix of smaller aircraft. A schedule based on actual 1988 traffic was augmented to the forecast 1995 traffic level to assure a sufficiently high demand level to saturate the runways at the reduced separations used. Figure 2-1 shows this runway configuration.

2.2 Sea-Tac International Airport (SEA)

SEA was also used for experiments involving multiple runway crossings and multipath runway exits. These experiments used a configuration that incorporates a proposed third parallel 5000-foot runway, 15/33, west of the existing two north/south runways. This configuration was run in VFR, south flow, with large arrivals on runway 16R, and smaller aircraft on the proposed shorter outboard runway 15. Large departures used inboard runway 16L, while smaller departures used mixed runway 15. Crossing gaps were opened on runways 16R and 16L to allow runway 15 arrivals to reach the terminal without excessive delay. This is also necessary to assure that the crossing queues did not block the exits of runway 15. Figure 2-2 shows this runway usage.

2.3 Dulles International Airport (IAD)

IAD was used for experiments involving multiple departure queues, multiple runway exits, and multipath taxiways to gates. The airport geometry used for the simulation experiments was adapted from the ultimate master plan for this airport. However, for the experiments involving multiple departure queues and multiple exits, only the existing runways were used.

The baseline configuration used for multiple departure queues is shown in figure 2-3. The airport is operated to the south under VMC conditions with arrivals on 12L, departures on 19L, and mixed on 19C. The configuration used for
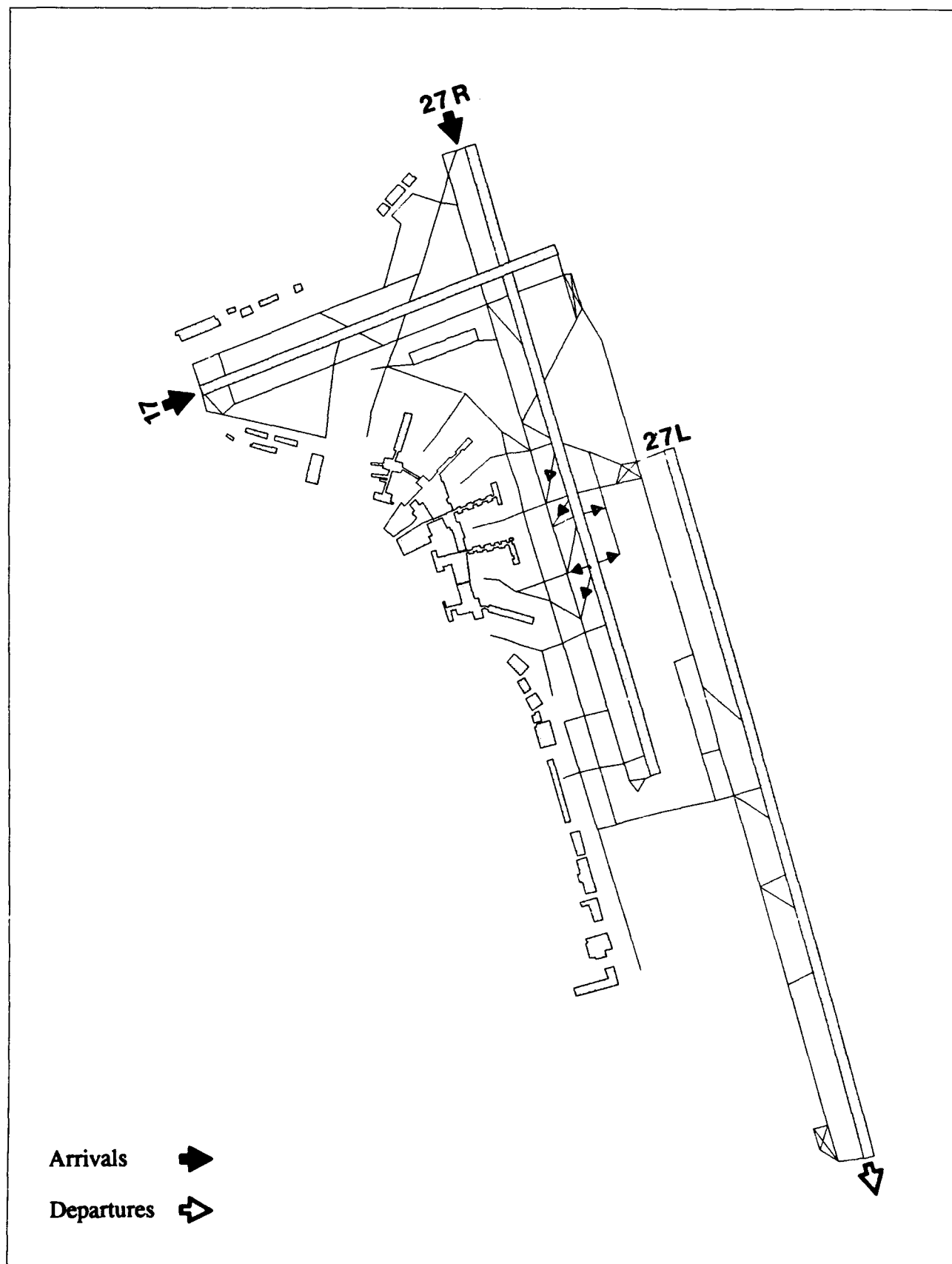
27R

27L

17

Arrivals ➤

Departures ⇨

Fig. 2-1   PHL Runway Configuration
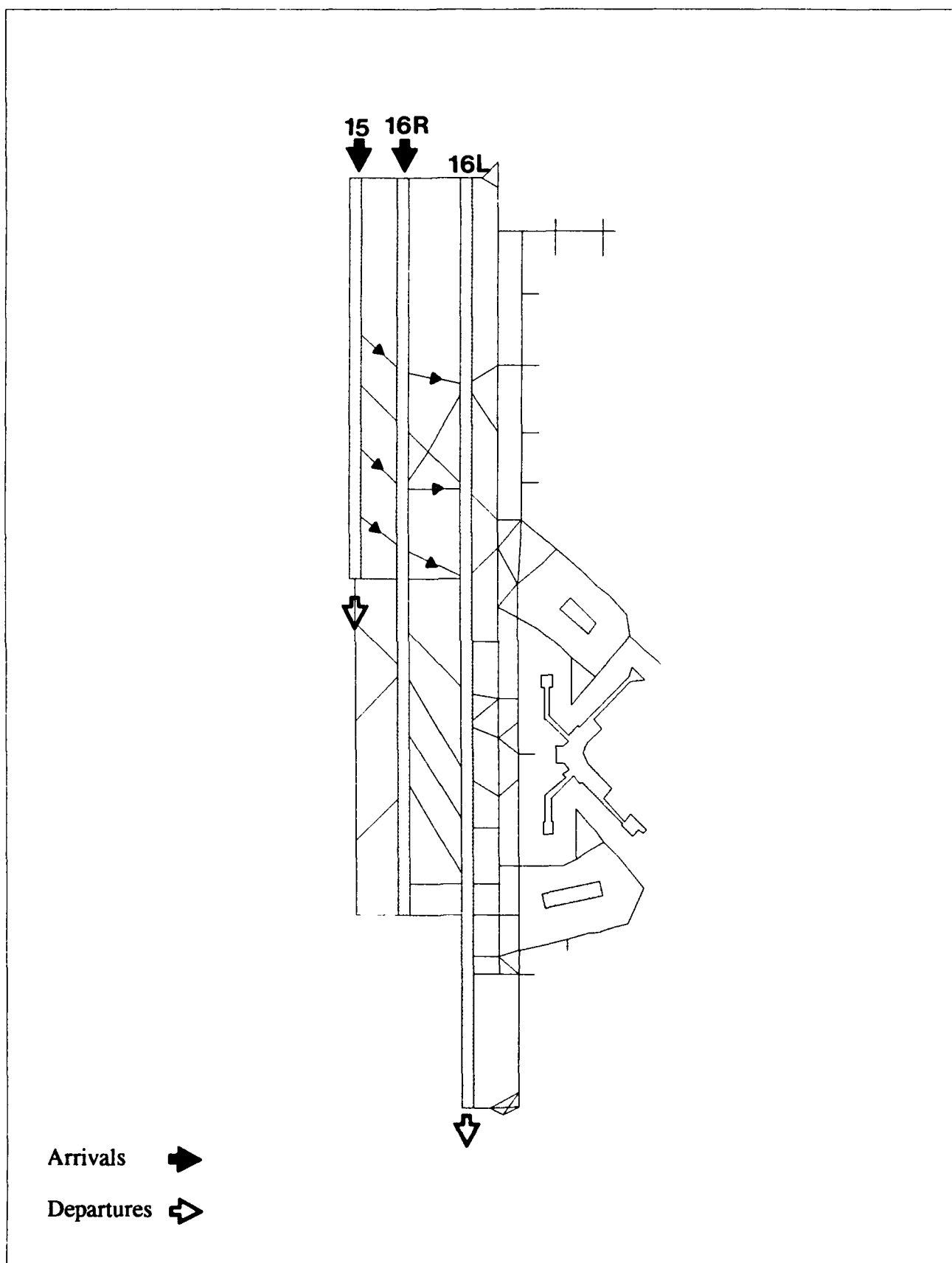
6

15 16R

16L

Arrivals ➡

Departures ⇨

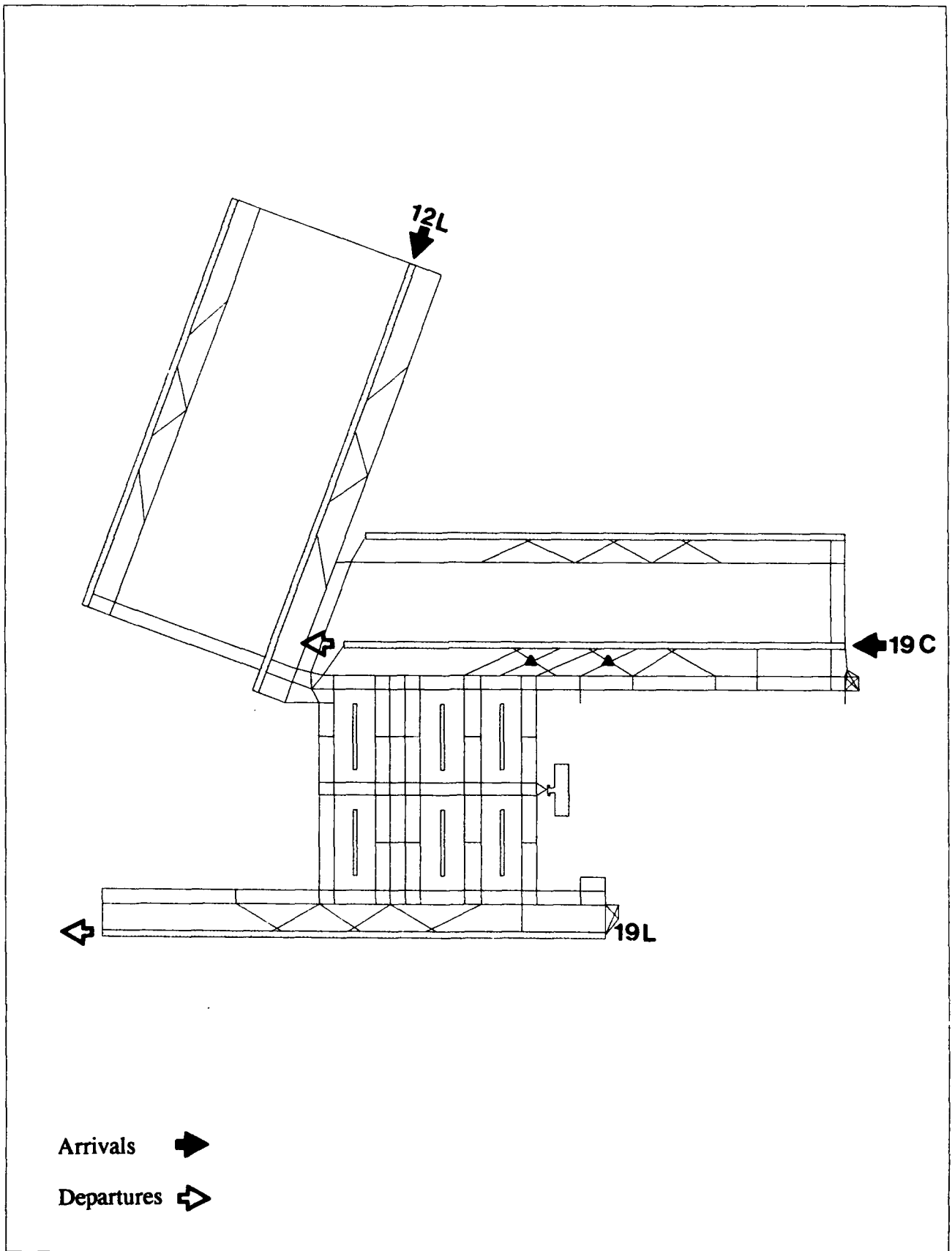Fig. 2-2   SEA Runway Configuration

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Fig. 2-3   IAD Runway Configuration

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the multiple exit experiments is the same, except that there are no departures on 19C. For the experiments on multipath taxiways to gates, the full complement of runways was used in order to reach the traffic levels needed to exercise the multipath taxiway system.

2.4 Dallas - Fort Worth International Airport (DFW)

DFW was used for experiments to evaluate multiple departure queues and multipath runway exits. The baseline database was taken from the two recent studies performed for the DFW Airport Board. The geometry incorporates three possible future airport enhancements:

- northern extensions of the north/south runways

- a new parallel runway on the east side

- a new American Airlines terminal on the west side.

For these experiments south operation was used with outboard existing north/south runways 18R and 17L as the primary arrival runways and the inner runways, 18L and 17R, as primary departure runways. Figure 2-4 shows the runway usage at DFW.

2.5 The New Denver International Airport (DIA)

DIA was used for experiments involving multipath runway exits. The geometry of the ultimate airport master plan was used in the simulation; however, only the six runways planned for the initial phase of construction are used in the experiments. These runways are operated to the southeast and assume VMC conditions. Arrivals were assigned to runways 17C and 17L on the west side of the airport. Departures were assigned to runways 18L, 18R, and 9R on the east side of the airport. Figure 2-5 shows runway usage at DIA.

2.6 Kennedy International Airport (JFK)

JFK was used for experiments to evaluate multipath runway exits. VMC conditions and southeast flow were assumed for these experiments. The primary arrival flow was to runway 22L with secondary flow to 13R. All departures used runway 22R. It would be desirable for arrivals on 13R to be independent of departures on 22R so as to eliminate the requirement for gaps in the arrival stream to facilitate departures. Considering that runway 22R crosses runway 13R almost 10000 feet from the displaced threshold, it was assumed that with the additional exits in place any aircraft arriving on runway 13R would be able to exit before the runway 22R crossing. It was assumed, therefore, that flights arriving on 13R would hold short of the runway 22R crossing so that departures on 22R would be independent of 13R arrivals (although this does not appear to be the current operating procedure). Figure 2-6 shows runway usage at JFK.

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18R

18L

17L

17R

Arrivals
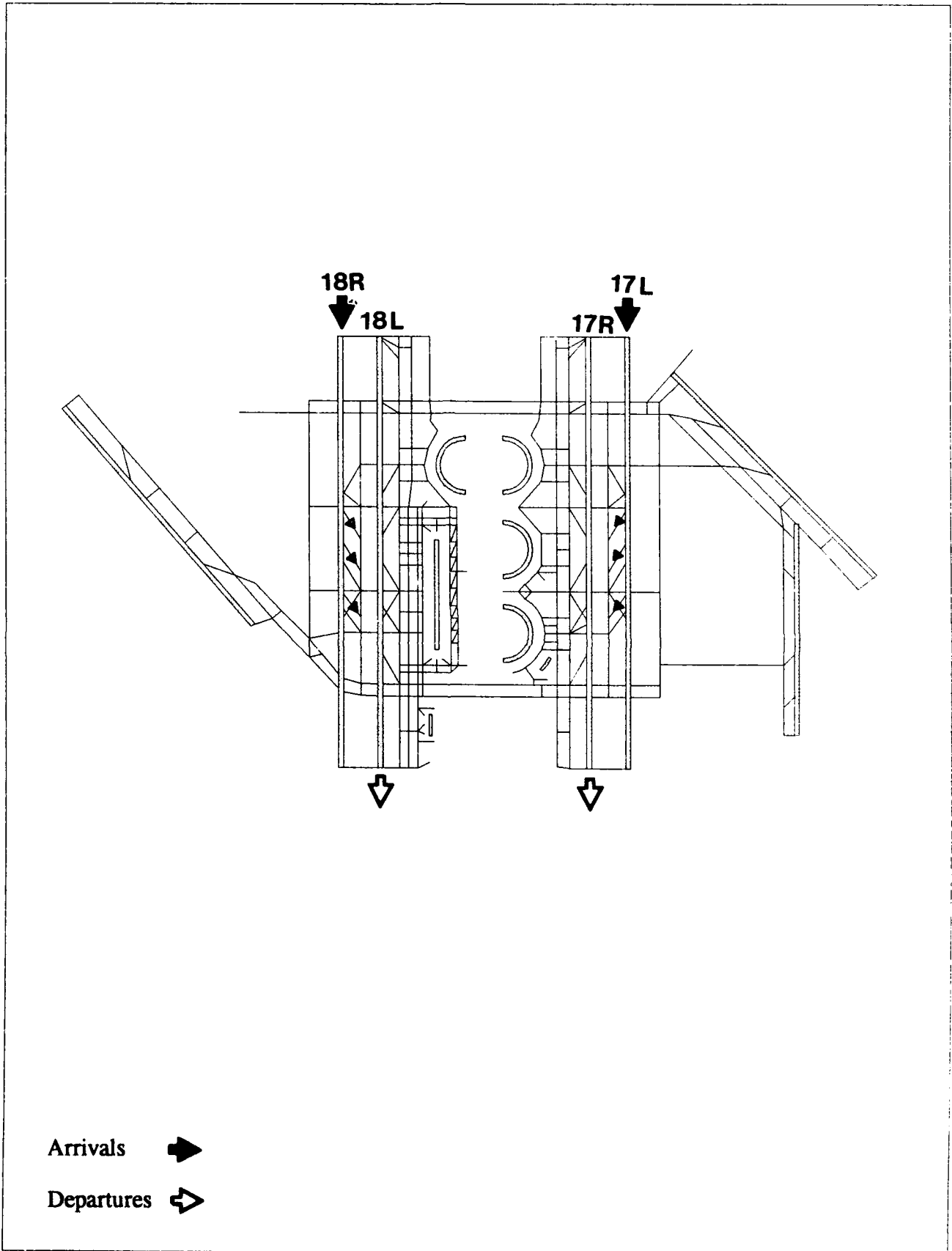
Departures

Fig. 2-4   DFW Runway Configuration

17L

17C

9R

18 L

18R
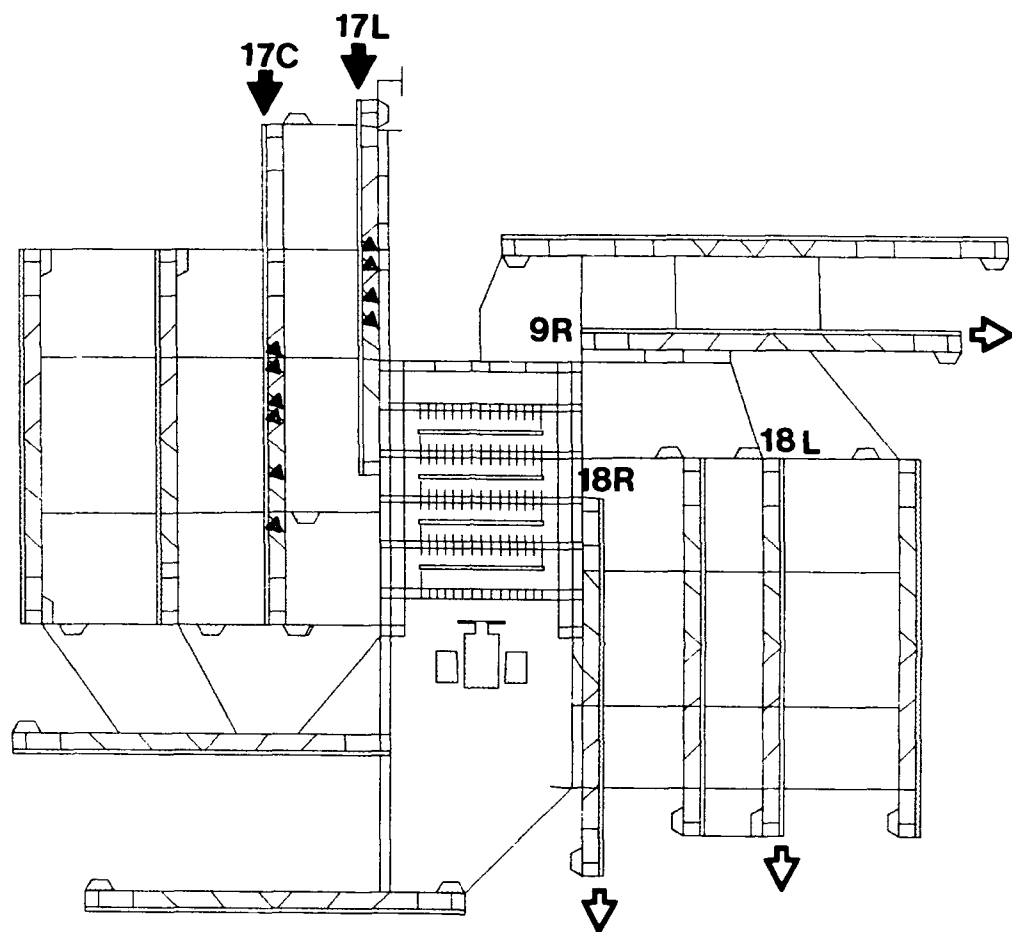
Arrivals ➡

Departures ⇨

Fig. 2-5   DIA Runway Configuration

11

13R

22R

22L
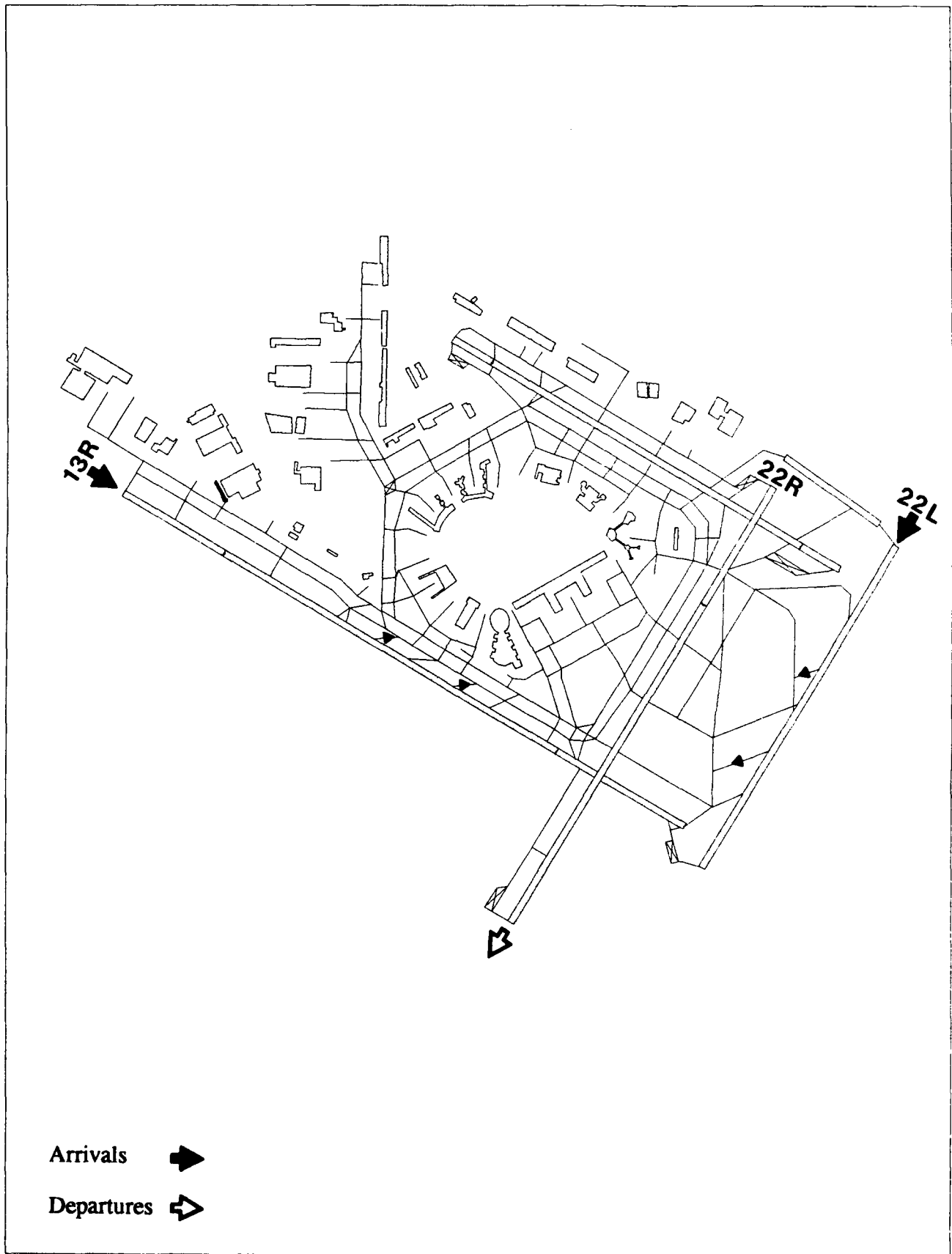
Arrivals ➡

Departures ⇨

Fig. 2-6   JFK Runway Configuration

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3. Multiple Taxiway/Runway Crossings

This section will describe the multiple taxiway/runway crossing concept along with the simulation experiments performed and the results obtained.

3.1 Description of the Multiple Crossing Concept

When an arrival or departure runway is being used at capacity, it may be necessary to interrupt the sequence occasionally to permit taxiing aircraft to cross the runway. To maximize runway throughput, it is therefore necessary to minimize the frequency and duration of these crossing gaps. By using multiple parallel crossing points, several aircraft can cross at once thus reducing the number of gaps required and/or the time required to cross all waiting aircraft.

In addition to reducing the number of queued aircraft, the use of multiple crossing points also has the advantage of distributing the crossing queues along the length of the runway and making the individual queues smaller and easier to manage. This minimizes secondary taxi delays due to the congestion caused by these queues.

Care must be taken, however, in the evaluation of delay savings that result from use of multiple crossing points (as subsequent simulation results will show). If other flow constraints exist downstream of the crossing points, then crossing delay may be reduced only to be offset by increases in delay at other points in the system.

3.2 Airport Configurations Simulated

The subject airports for the multiple taxiway/runway crossing experiments were Philadelphia International Airport (PHL) operating west-south, and Sea-Tac International Airport (SEA) operating in south flow.

3.2.1 PHL Experiments

For PHL, crossings were added to provide multiple crossings over runway 27R during each gap in the arrival stream. This is to ensure that departures taxiing out from the terminal area are not delayed crossing runway 27R to depart on 27L. Figure 2-1 shows the taxiway geometry used with arrows depicting the added crossings. Experiments were run for configurations with and without the subject crossings. To ensure minimal congestion on the inboard parallel taxiways, gaps were opened in the 27R arrival stream whenever there were three or more flights waiting to cross.

3.2.2 SEA Experiments

For SEA, crossings were provided for flights arriving on the proposed multipath exits of runway 15 to allow for crossing over runways 16R and 16L to taxi in to the terminal area. Figure 2-2 shows SEA with arrows depicting the added exits and crossings. As can be seen, if the proposed multipath exits at SEA were to be used, then the proposed

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additional crossings would seem necessary also. Therefore, simulations were performed for SEA configurations with and without both the proposed exits and crossings. Gaps were opened in the arrival and departure streams of runways 16R and 16L if one or more flights were waiting to cross. This ensured that the exits of runway 15 were cleared as rapidly as possible.

3.3 Analysis of Results

3.3.1 PHL Results

Figure 3-1 shows a comparison of taxi and runway delays for PHL with and without the proposed multiple crossings in place. Adding multiple crossings decreased taxi-out delay, runway crossing delay, arrival runway delay, and taxi-in delay. However, the decrease in these delays was partially offset by increased departure runway delay. The existing crossings at PHL appear to be adequate to feed runway 27L with departures at about the current departure rate. However as departure/departure separation intervals decrease in the future, the benefits of the increased crossing capacity will become even more pronounced. Taxiway/crossing delay diagrams for PHL showing the locations on the taxiway system where these delays occur, with and without multiple crossings, are shown in figures 3-2 and 3-3. In these figures, the areas of the shaded circles are proportional to the delay absorbed at the intersection.

3.3.2 SEA Results

The SEA experiments showed that multiple exits and associated multiple crossings were required for the proposed new runway due to the limited space to queue the arrivals waiting to cross the adjacent runway. If the proposed exits are not provided, the other exits tend to become full and an excessive number of arrivals on that runway must be aborted. For instance, during the 12 o'clock hour of the baseline simulation using standard separations, four go-arounds were required out of 12 total runway 15 arrivals, whereas the simulation employing the proposed exits and crossings yielded only one go-around during the entire 24-hour period.

Since the operation of runway 15 without multiple runway exits did not appear to be feasible, it was not possible to make a valid comparison of delay with and without multiple exits.
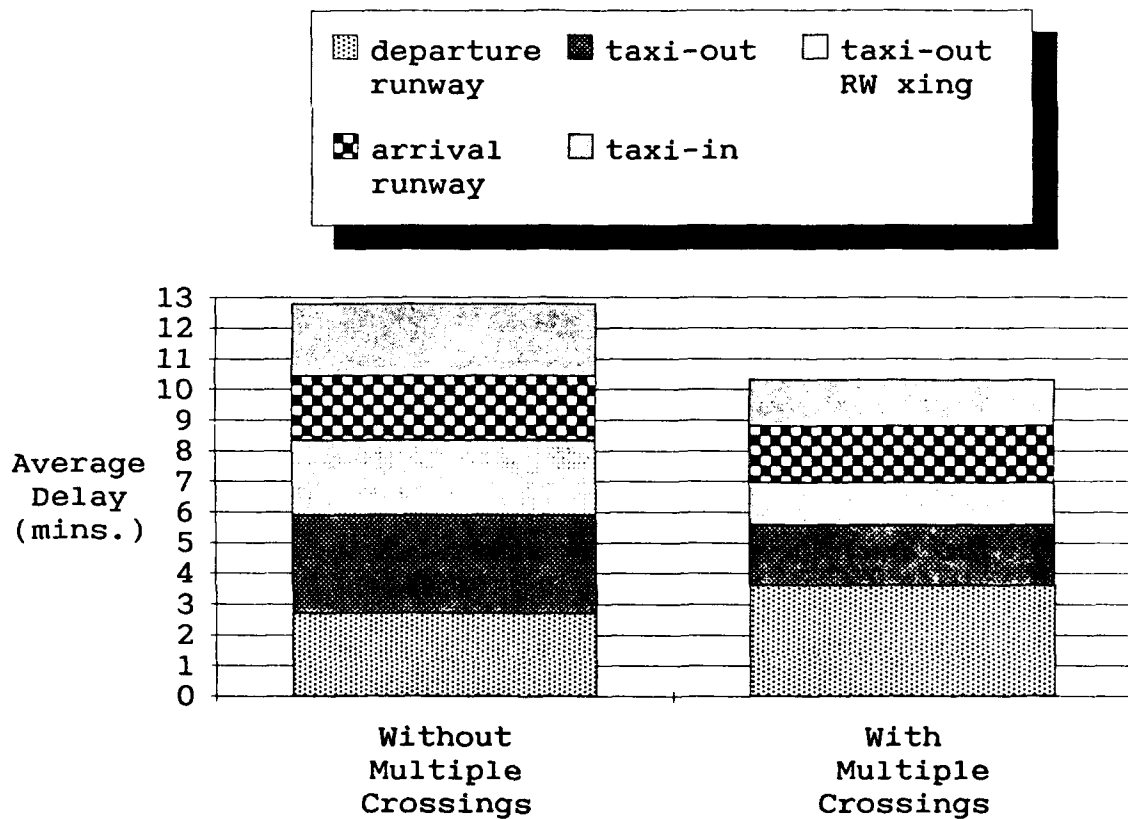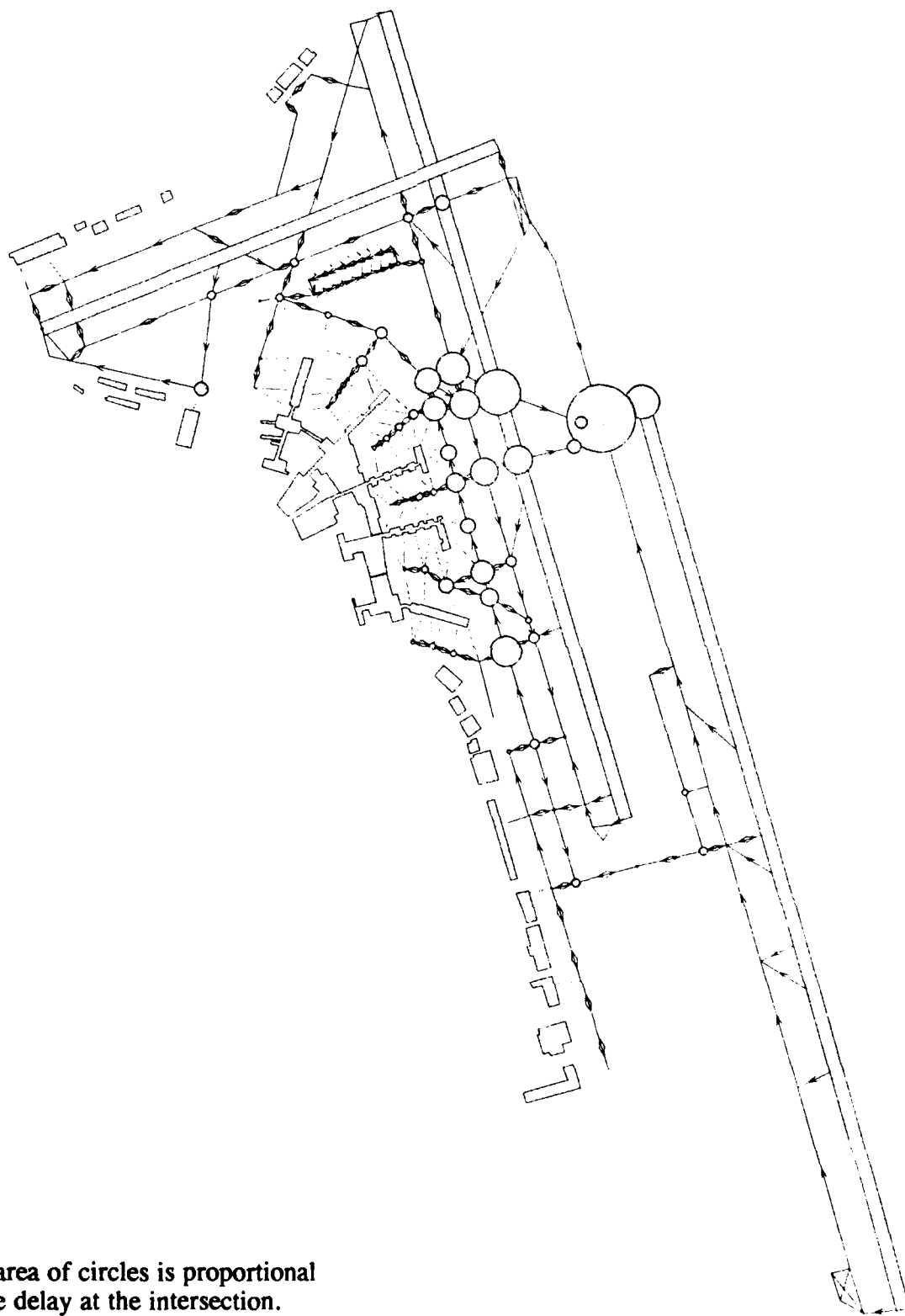
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Fig. 3-1

PHL Delay Reduction Due to Multiple Crossings

The area of circles is proportional
to the delay at the intersection.

Fig. 3-2
Runway/Taxiway Crossing Delay for PHL Baseline Configuration

The area of circles is proportional
to the delay at the intersection.
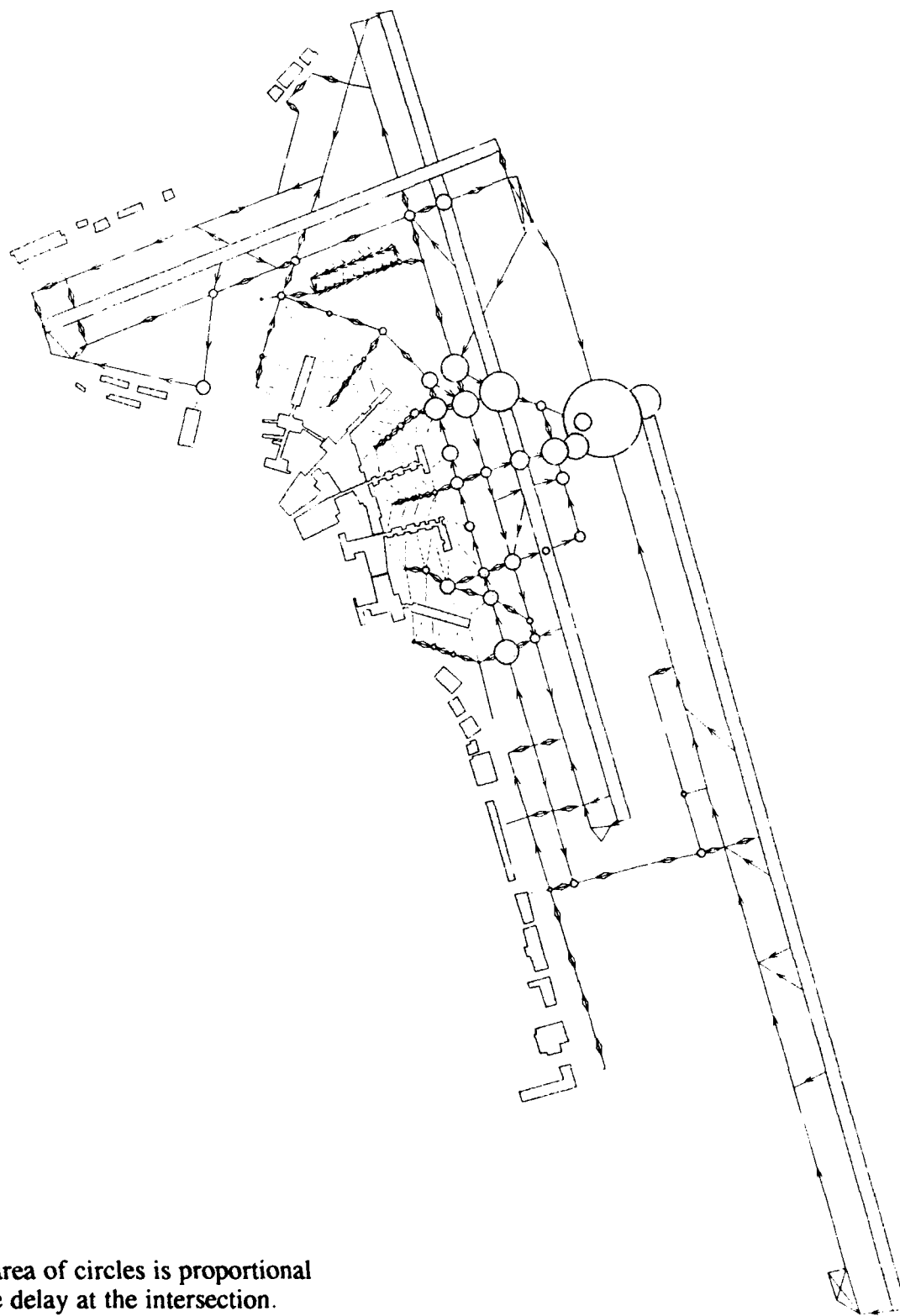
Fig. 3-3
Runway/Taxiway Crossing Delay for PHL Multiple Crossings Configuration

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4. Multiple Departure Queues

This section will describe the multiple departure queue concept along with the simulation experiments performed and the results obtained.

4.1 Description of Concept

Multiple departure queues are used in lieu of the usual single departure queue to provide enhanced flexibility in sequencing departures.

This sequencing flexibility is important in order to maximize the departure throughput of the airport since the spacing between pairs of departures is frequently dependent on characteristics of the two flights such as:

    (a) wake turbulence category

    (b) climb speed

    (c) intended departure route

    (d) noise classification.

The departure/departure constraints may be imposed on pairs of flights on the same runway or pairs of flights departing on any runway headed to the same or crossing departure route.

Each of these types of departure/departure constraints is reviewed briefly in the discussion below.

4.1.1. Departure/Departure Constraints

(a) Wake Turbulence Classification
Wake turbulence separation minima are imposed between pairs of aircraft on the same or crossing departure routes that do not have 1000-foot vertical separation. The separations are based on the weight classifications of the aircraft as follows:

    - heavy behind heavy   4 nm

    - large behind heavy   5 nm

    - small behind heavy   5 nm

Pairs of departures from the head of the same runway are subject to this constraint until their paths diverge or a 1000-foot altitude separation is achieved.

When sequencing departures, therefore, a higher throughput can be achieved by avoiding alternating of heavy and small aircraft.

(b) Climb Speeds Category
When aircraft are departing on the same departure path, the minimum separation at any point along the common path is 3 nm, or greater, if the additional wake turbulence constraints discussed above are imposed. Therefore, a substantial delay may occur before a fast aircraft can be released behind a slow one that uses the same departure path.

(c) Intended Departure Route
In addition to the minimum separation between pairs of aircraft departing on the same runway, minimum in-trail separation times are frequently imposed by en-route ATC control on flights leaving the airport terminal area via the same route or departure gate. In severe cases, such as might be caused by thunderstorm activity, the acceptance rate might drop to zero for a particular airspace direction. It is often desirable, therefore, to be able to interleave other flights between flights going to the same departure route, or to suspend all flights going in a particular direction.

(d) Noise Classifications
The delays due to interleaving of fast/slow aircraft and wake turbulence classes can sometimes be avoided by diverging the paths of the flights as soon as possible after takeoff so that they are not on the same climbout path. This may not be possible for all classes of aircraft, however, due to noise constraints on the use of certain paths. It is important therefore to have the flexibility to interleave lower-noise flights, such as certain commuter types, with the other flights.

4.1.2. Implementation of Multiple Departure Queues

While the essential purpose of multiple departure queues is to provide flexibility in the sequencing of departures, there are a number of possible physical implementations of these queues. They may take the form of parallel taxiways (with possible crossover links) upon which the departures are queued, or large paved aprons, or a combination of these taxiways and aprons.

For purposes of investigating some of the generic properties of these two types of implementations, a highly simplified test case has been hypothesized for which:

- all flights are of the same (large) aircraft type

- flights are assigned randomly with equal probability to one of the available routes

- the in-trail minimum time permitted between flights going to the same route is 5 minutes

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- the in-trail time between flights not in the same route is one minute.

For these analyses, the available distinct routes are called departure streams and the number of these streams, NSTRM, is varied in the analysis.

4.1.3. Apron Implementation

Multiple departure queues can be implemented as aprons located near the departure end of a runway. These aprons (sometimes called hammerheads) permit the storage and bypassing of a given number of flights. The effectiveness for the test case again depends on the number of streams and the size of the apron, as summarized at the top of figure 4-1, where the resulting runway throughput is plotted against the number of available departure streams.

When the capacity of the smallest size apron is a single flight, the throughput is the same as for a single parallel path. The more streams that are used, the less likely it is that flights using the same stream (requiring greater separation) will occur randomly in the sequence produced.

As the capacity of the apron is increased to accommodate eight flights, the throughput approaches the theoretical maximum of 60 departures per hour as indicated by the straight lines bounding the upper edges of the plot.

4.1.4. Parallel Taxiways Implementation

When parallel taxiways are used to implement multiple departure queues, the controller may select any of the flights that are at the head of one of the parallel taxiways as the next departure. If there are three parallel taxiways, therefore, he would have the choice of three flights. Typically the ground controller would sort the departures to these parallel taxiways based on airspace direction, or possibly also on wake turbulence classification.

For the test case the flights were sorted by departure airspace stream. The results of the simplified simulation test are shown at the bottom of figure 4-1. The number of parallel paths used, NPTHS, is varied parametrically from 1 to 6.

When the number of parallel taxiway paths equals or exceeds the number of airspace streams, the maximum possible throughput is reached. For fewer paths than streams, the throughput is always increased by increasing the number of paths.

While the comparisons shown in figure 4-1 are interesting from the point of view of illustrating the basic principles, the best solution for a particular airport cannot be determined from this simplified analysis. An actual implementation would most likely consist of a mixture of parallel taxiways, crossovers, and aprons specifically designed for the geometry and operational requirements of the particular airport and runway. The evaluation of two possible actual implementations is described in the next section.
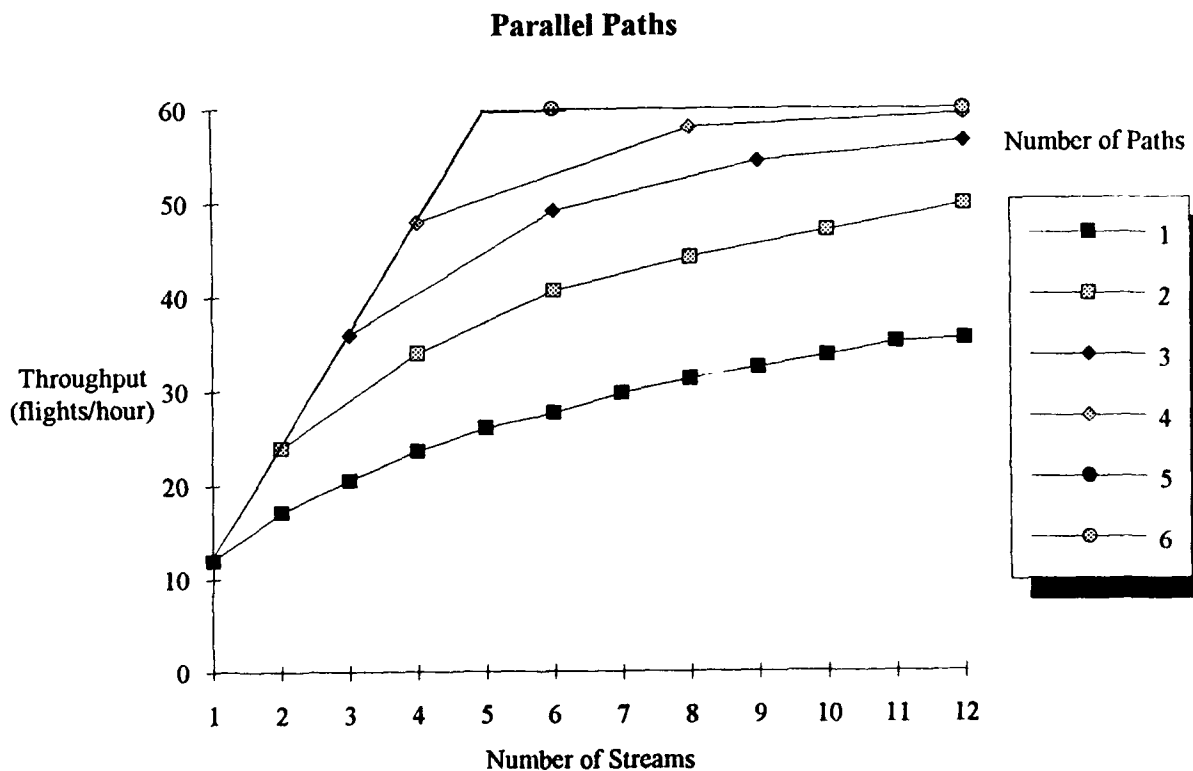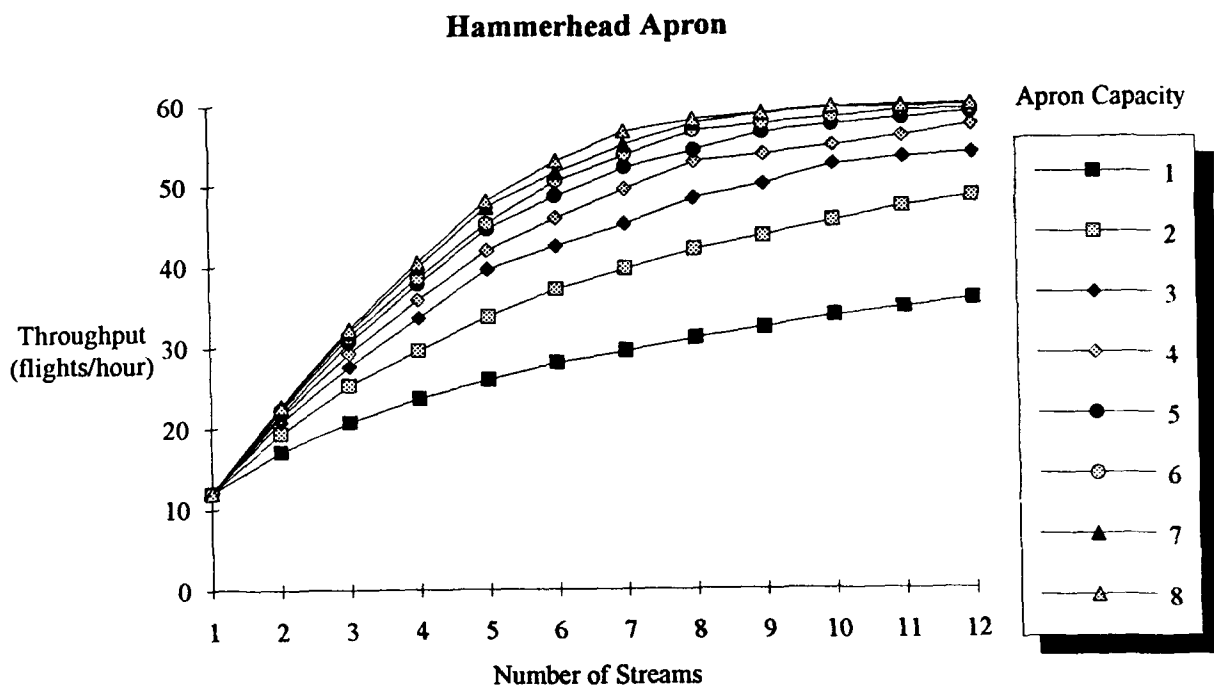
20

Fig. 4-1   Multiple Departure Queue Parameter Sensitivity

4.2 Description of Experiments Performed

Both types of multiple departure queues were simulated using The Airport Machine: hammerhead aprons and parallel paths.

4.2.1 IAD Experiments

Dulles Airport used (hammerhead) aprons at the heads of departure runways. Its schedule contained flights from four different streams. Four separate runs were performed varying apron size[1] at departure runway heads. The apron capacities were modeled to handle one, two, four and six flights.

To illustrate the value of multiple queues in a situation where there are in-trail separation restrictions, the required in-trail separation of flights going to the same stream was set to five minutes. Flights to unlike streams have no in-trail dependencies.

4.2.2 DFW Experiments

On the other hand, for the case of Dallas-Fort Worth Airport, queues were implemented by the use of three parallel paths leading to the head of the departure runways. Two runs were performed, one with, and one without, the use of these multiple taxiway paths. Departing flights were assigned to one of the taxiway paths in accordance with airspace stream. Each of the three taxiway paths, in turn, was assigned to process flights to a specific subset of the streams. Since the schedule used as input to the simulation contained flights departing in seven different streams, one path was assigned three of the streams, while the other two paths were assigned two streams each.

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[1] The Airport Machine models apron size in terms of equivalent linear feet of queuing distance along a taxiway.

4.3 Analysis of Results
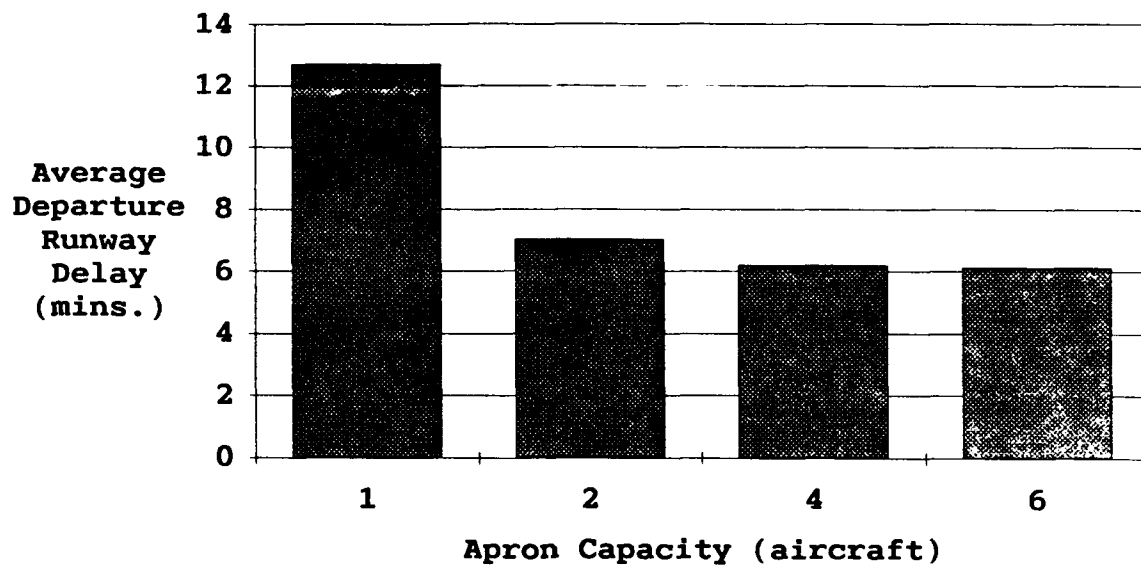
4.3.1 IAD Results

With hammerhead aprons at IAD, improvement in departure delay levels off as the apron capacity approaches the number of streams being served. Therefore, for maximum throughput, the apron capacity should be equal to the number of streams. Figure 4-2 illustrates how average departure delay is affected by an increase in apron capacity for both mixed and departure-only runways at IAD. Figures 4-3 and 4-4, respectively, show how the runway delay is distributed on the taxiways at IAD for configurations without hammerhead aprons, and with aprons large enough for four flights. As can be seen, delay with hammerhead aprons is smaller and is concentrated at the departure runway heads, thus freeing up inner taxiways for normal traffic.

4.3.2 DFW Results

At Dallas-Fort Worth Airport, throughput tests were performed with and without ordering of departures using the three existing paths to each of the two departure runway heads. In this case, as shown in figure 4-5, average departure delay was decreased by approximately 57 percent. Figures 4-6 and 4-7, respectively, show taxiway/crossing delay for configurations with and without the use of multiple departure queue paths. Again, crossing delay is evident within the terminal area for the single queue configuration. However, this delay is reduced by the use of multiple departure queues.

DULLES INTERNATIONAL AIRPORT

19L (Departures Only)

Average Departure Runway Delay (mins.) vs Apron Capacity (aircraft)

19C (Mixed Operations)

Average Departure Runway Delay (mins.) vs Apron Capacity (aircraft)

Fig. 4-2   IAD Delay Reduction Due to Multiple Departure Queues

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The area of circles is proportional
to the delay at the intersection.

Fig. 4-3   IAD Runway/Taxiway Delay Without Multiple Departure Queues

The area of circles is proportional
to the delay at the intersection.

Fig. 4-4   IAD Runway/Taxiway Delay With Multiple Departure Queues
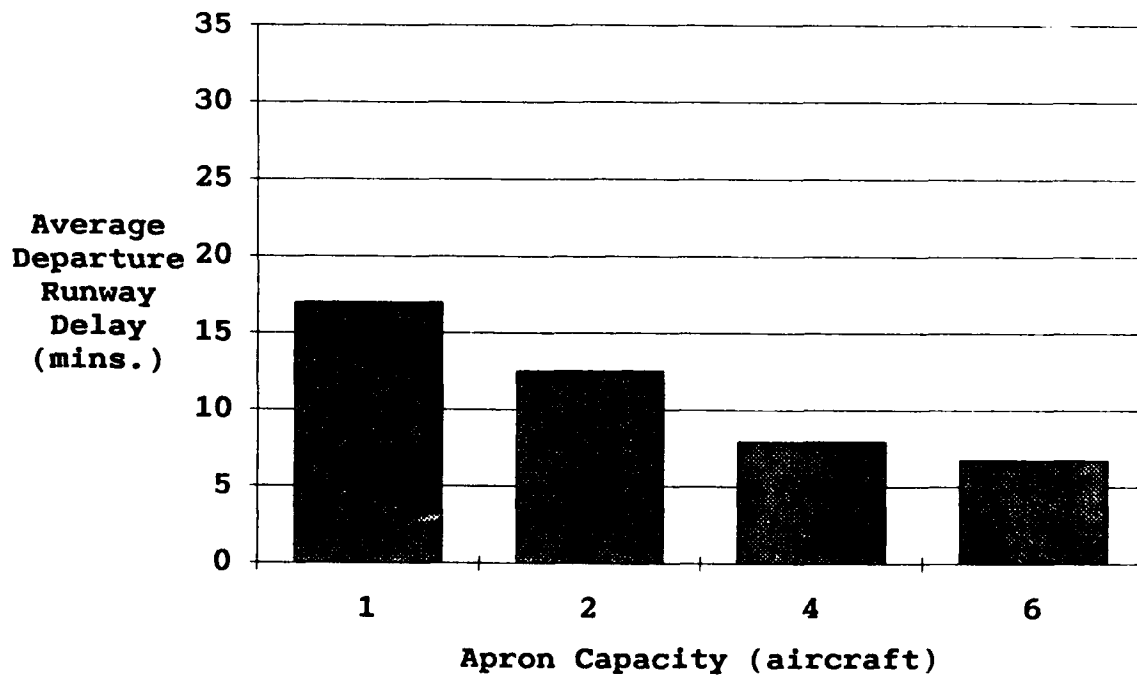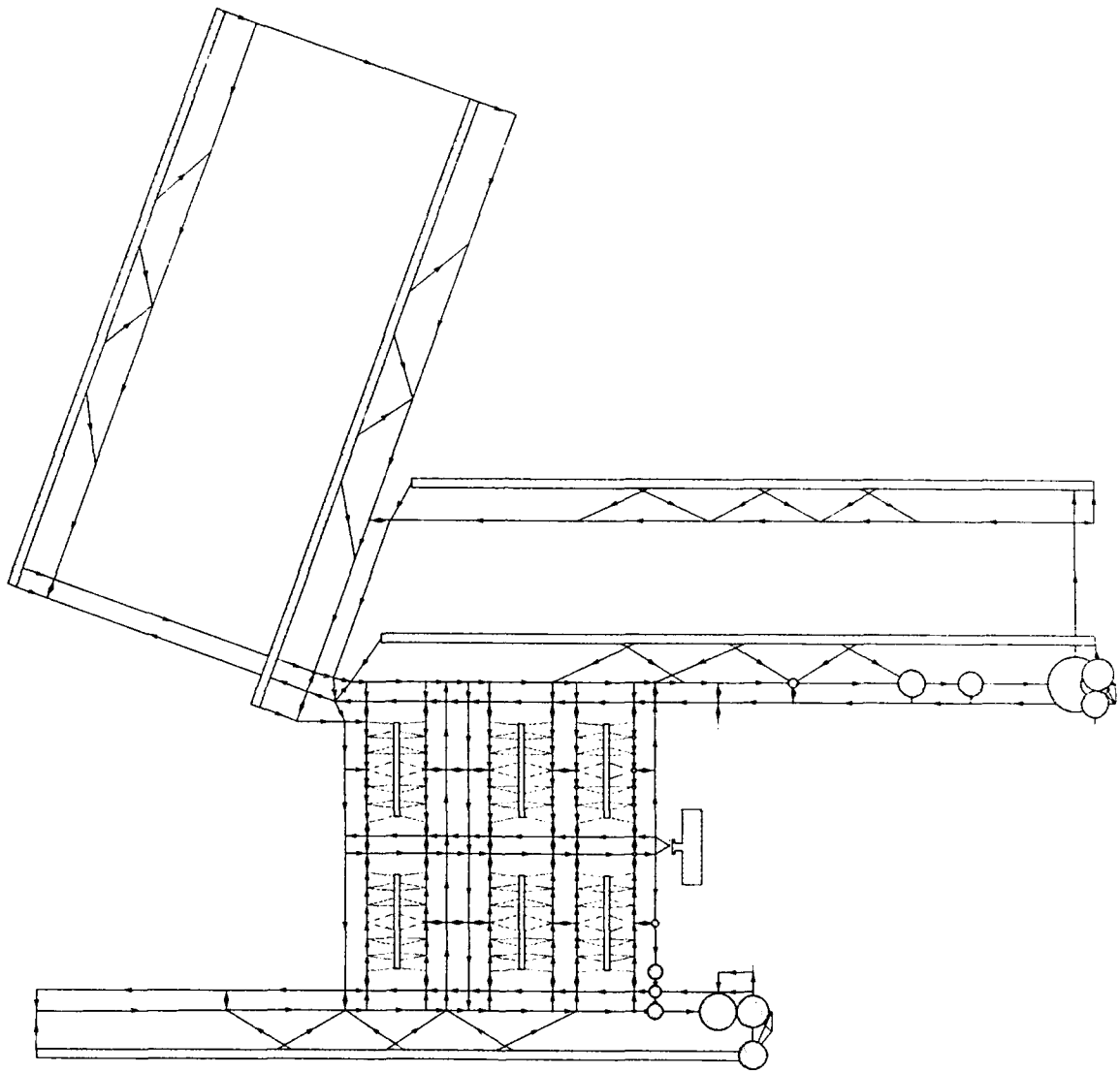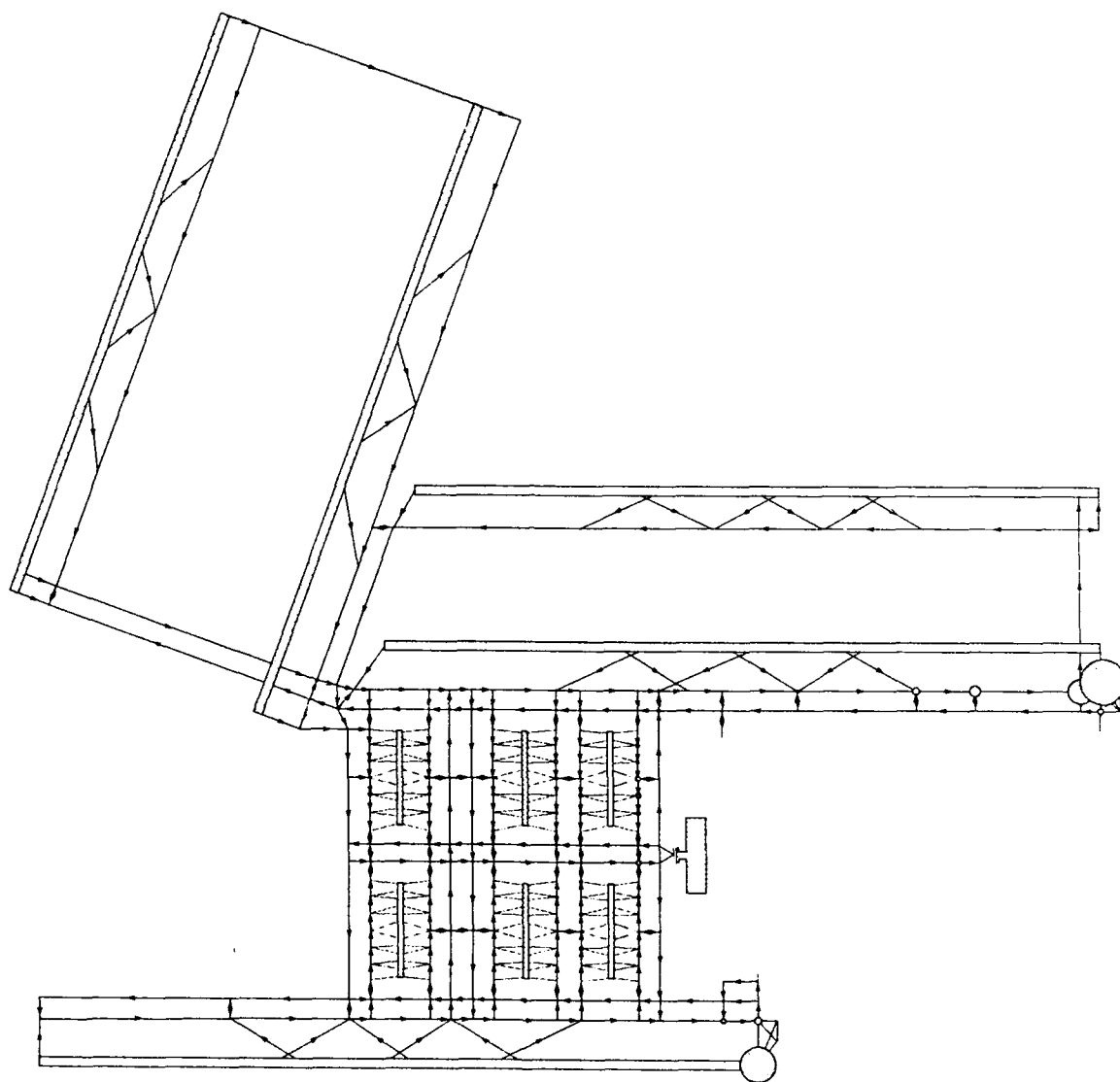
DALLAS-FORT WORTH INTERNATIONAL AIRPORT

Fig. 4-5   DFW Delay Reduction Due to Multiple Departure Queues

The area of circles is proportional to the delay at the intersection.

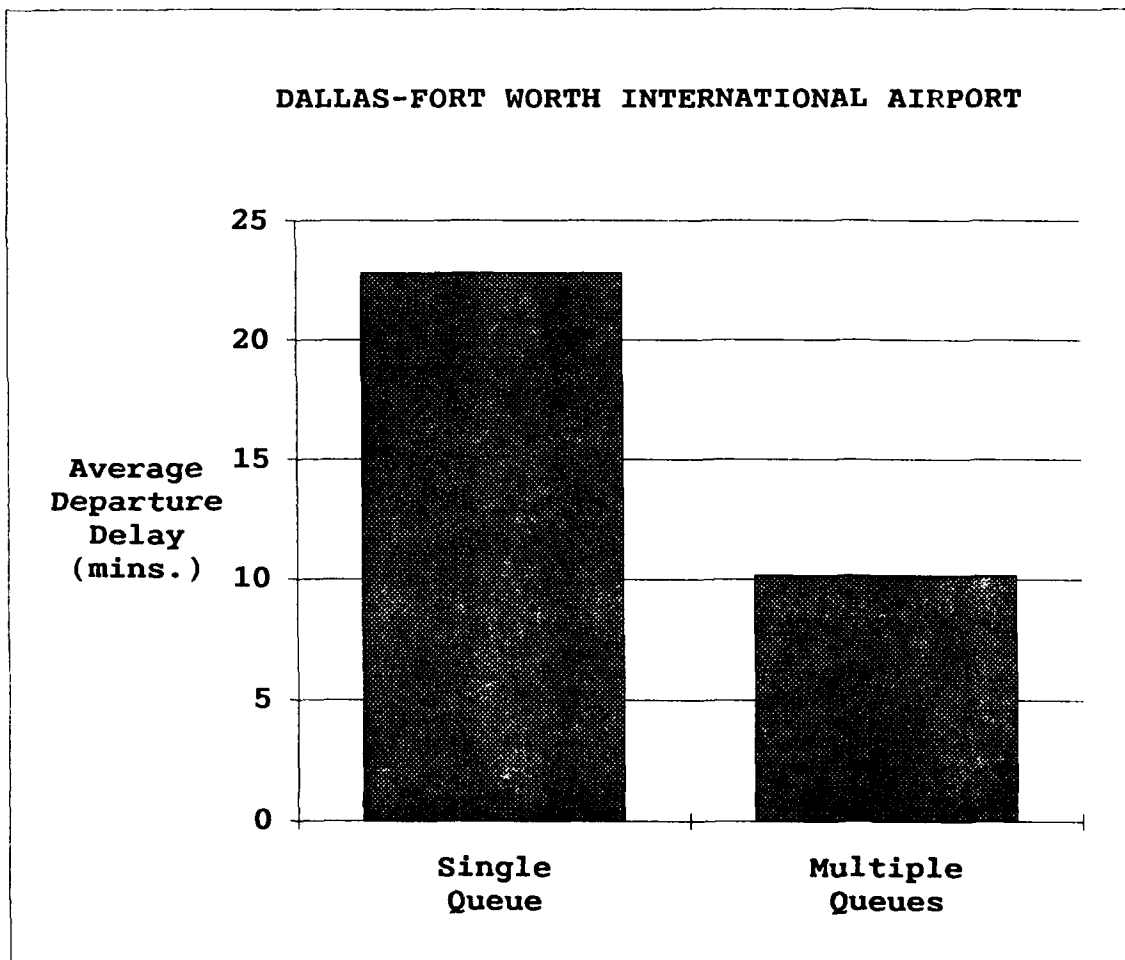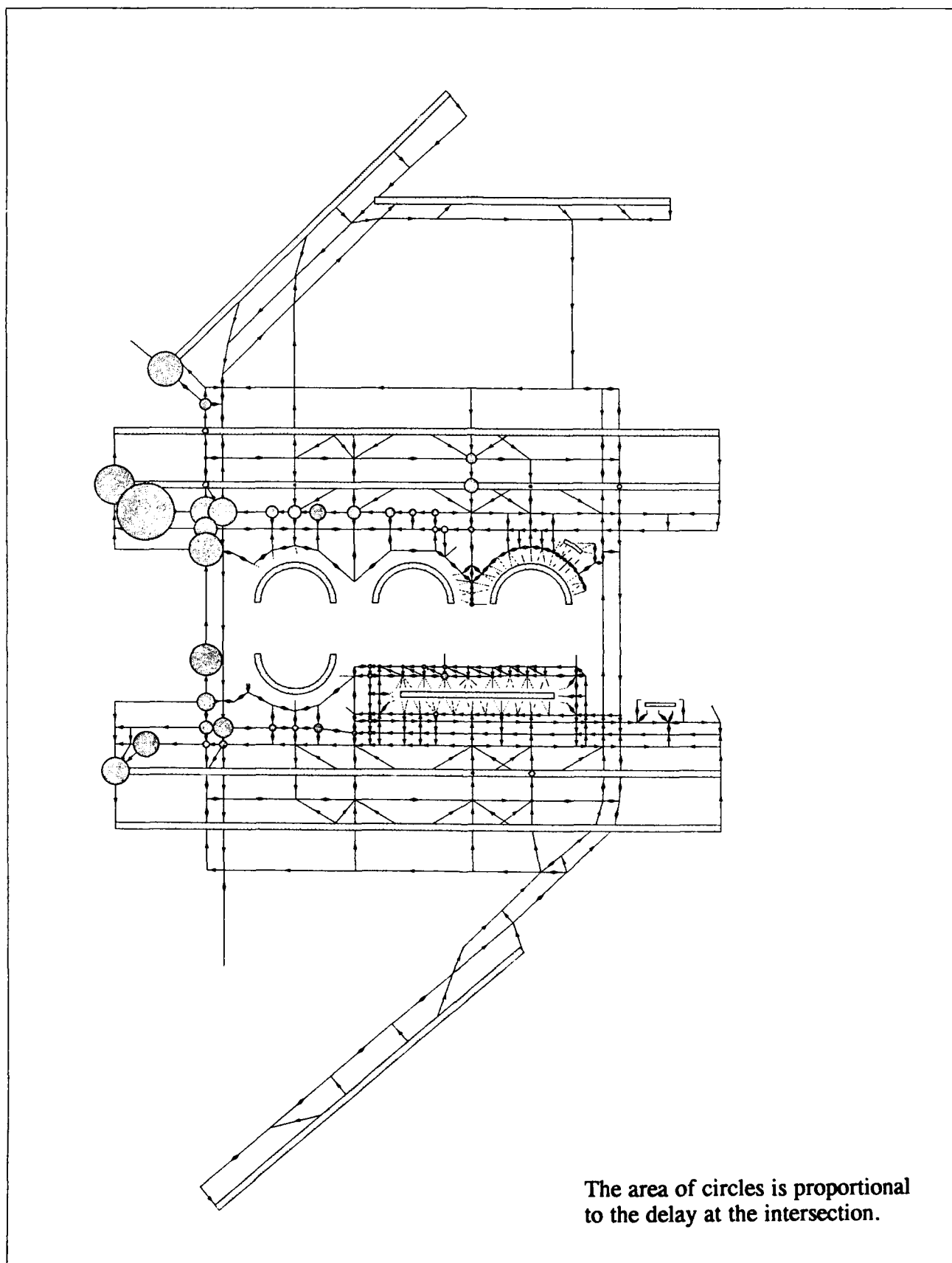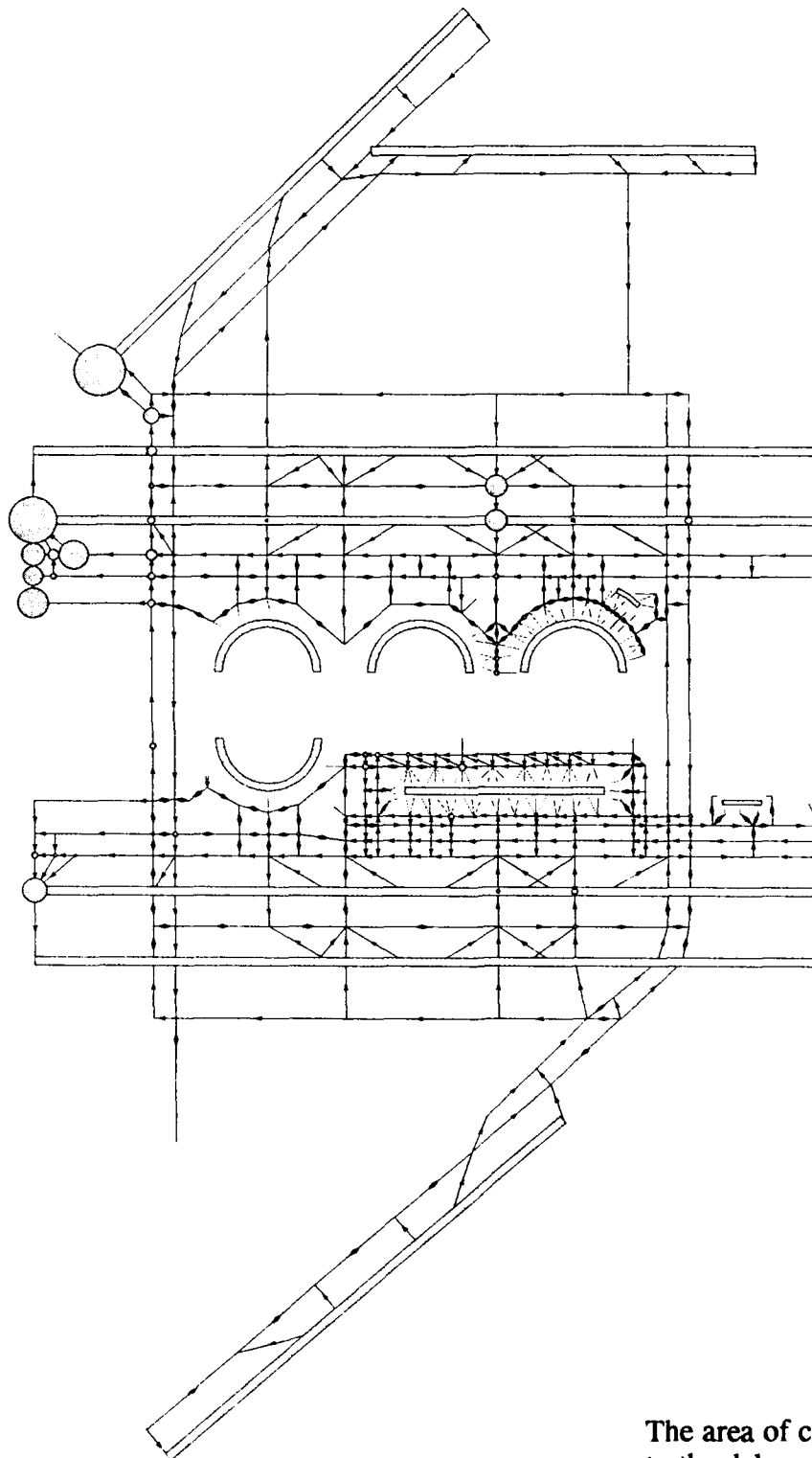Fig. 4-6   DFW Runway/Taxiway Delay Without Multiple Departure Queues

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The area of circles is proportional to the delay at the intersection.

Fig. 4-7   DFW Runway Taxiway Delay With Multiple Departure Queues

5. Multipath Runway Exits

This section will describe the multipath runway exit concept along with the simulation experiments performed, the results obtained, and the sensitivity of these results to variations in fleet mix.

5.1 Description of Concept

The throughput of a runway operating in the arrivals-only mode is inversely proportional to the average time between successive threshold crossings. Since the preceding arrival must be clear of the runway when an arrival crosses the threshold, the runway occupancy time[2] (ROT) places an upper bound on the throughput that can be achieved as arrival/arrival separations are reduced in the future.

Likewise, for runways operating in mixed arrival/departure mode, a waiting departure can not start roll until the preceding arrival is clear of the runway. In this case, ROT is already a limiting factor even with today's separation standards.

The average ROT of a runway can, in general, be reduced by increasing the number of exits (so that an exit is available at the earliest location) and by using exit geometries that permit the aircraft to exit at higher speeds.

If an exit is not available at the minimum distance (natural location) based on deceleration, then the pilot will generally delay his final deceleration by coasting until he is within range of the available exit[3]. This effective coast speed determines the sensitivity of ROT to the spacing between exits. Table 5.1 shows typical sensitivity factors for a range of exit spacings and effective coast speeds. As this table shows, increasing the number of exits beyond a certain point yields diminishing returns in reducing ROT.

Table 5.1 Expected Value of ROT Increase (seconds)

Effective Coast Speed	Distance Between Exits (ft)				
	1000	1500	2000	2500	3000
40 kn	7.4	11.1	14.8	18.5	22.2
50 kn	5.9	8.9	11.8	14.8	17.8
60 kn	4.9	7.4	9.9	12.3	14.8

---

[2] Runway occupancy time is defined as the time required for an arrival to clear the runway after crossing the threshold.

[3] The Airport Machine simulation models the arrival deceleration as a three stage process:

- deceleration from landing speed to coast speed

- coast

- deceleration to exit speed.

Exit speed is a function of aircraft category and the angle of the exit.

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The above table assumes that all the exits are available. If, however, the selected exit is already occupied by a preceding arrival, then the flight must bypass the exit and proceed to the next one. If it is some distance to the next exit, this occurrence could substantially increase his ROT and perhaps result in a missed approach. Therefore for runways adjacent to another runway or to a busy taxiway (that could impede exiting traffic), it may be desirable to provide additional exits. These exits can provide temporary storage for flights exiting the runway that can not immediately proceed into the taxiway system.

5.2 Description of Experiments

The potential improvements in performance attributable to implementation of the multipath exit concept were evaluated in terms of both throughput increase and delay reduction.

The experimental approach used was to evaluate throughput and delay with the existing (or currently planned) exits, and then again with the number of exits increased in accordance with the multipath exit concept.

Before each of these sets of tests was performed, the arrival/arrival spacings were experimentally reduced until an incursion[4] rate of approximately one percent was obtained.

It should be emphasized that the improvements in performance were due basically to the decrease in arrival separations. However, these are made possible by the additional exits. If, on the other hand, these arrival spacing reductions were not possible due to other factors, then the reported improvements in performance would not be obtained by just adding the exits. It should be noted that arrival separation minima that are due to wake turbulence criteria were not reduced.

All six subject airports were used to weigh the advantages of adding multipath exits. The data bases of these airports were first updated to employ the exit speed assignment feature which was added to the model after the original studies of the subject airports were performed.

Throughput tests were conducted by building up an arrival queue by temporarily using very large arrival-arrival separations. Then, when a large enough queue was formed, arrivals were permitted to land at maximum rate. The throughput was computed by averaging the number of flights that arrived each hour until the arrival queue diminished.

---

[4] A runway incursion was deemed to occur if an exit was not available or if an arrival had not started to turn off the runway when the next arrival was over the threshold.

Figures 2-1 through 2-6 show the six subject airport configurations with arrows depicting the added multipath exits.

5.3 Analysis of Results

The results for each of the six subject airports are described below, and illustrated graphically in figures 5-1 through 5-6. In each case, significant improvements are reported. In some cases, however, it would be necessary to make improvements in the taxiway system also to alleviate the congestion that results at these high flow rates.

5.3.1 Philadelphia International Airport (PHL)

At PHL, the outer runway, 27L, is generally used for departures and the inner runway, 27R, is used for arrivals. Departures must therefore cross or taxi around the end of 27R to depart on 27L. Since even with the current demand level, gaps must frequently be opened in the arrival stream to permit departures to cross, any reduction in arrival spacing would exacerbate the runway-crossing problem and force most departures to taxi around the end of the arrival runway.

Therefore, to test for the increase in arrival throughput that might be achieved with multipath runway exits, an arrivals-only schedule was used. Use of multipath exits increased throughput by 21 percent, from 86 flights to 104 flights, as shown in figure 5-1.

Using the proposed schedule for 1995, arrival delay was decreased by 24 percent from 2.1 minutes to 1.6 minutes.

5.3.2 Seattle-Tacoma International Airport (SEA)

At SEA, flights arriving on runway 15 must get a crossing gap between arrivals landing on runway 16R to taxi in to the gate area. While running the baseline case with only two exits on runway 15, it was frequently necessary to open gaps on runways 16R or to reduce the landing rate on runway 15 because no exits were available. With only one exit available for most equipment categories, only one arrival could land on 15 before requiring a gap on 16R. By adding multipath exits to runway 15 as well as the necessary crossings, more flights could cross 16R in the same gap, subsequently reducing the number of gaps necessary on runway 16R and/or increasing the number of flights that could land on runway 15 before the opening of gaps was necessary.

As shown in figure 5-2, average arrival delay was reduced 53 percent, from 1.1 minutes to 0.5 minutes, by adding the exits and crossings. It was, in fact, concluded that operation of the baseline case may not be feasible without additional exits or some form of buffer storage for arrivals exiting the proposed new runway. Therefore, The throughput comparison was not plotted for this case.

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5.3.3 Dulles International Airport (IAD)

Multipath exits were added to arrival runway 19C of IAD. An increase in overall arrival throughput of 8.4 percent, from 95 to 103 flights per hour, was thus gained with the addition of high speed exits to only one of the two operating arrival runways. Using a schedule to model the current demand at IAD, average arrival runway delay was decreased by 22 percent, from 1.4 minutes to 1.1 minutes, as shown in figure 5-3.

5.3.4 Dallas-Fort Worth International Airport (DFW)

Adding multipath exits to arrival runways 18R and 17L at DFW yielded a possible increase in arrival throughput of 20 percent. The baseline version produced a throughput of about 79 flights an hour, while multipath exits improved it to 95 flights an hour. Using a schedule to model the current demand at DFW, arrival runway delay was decreased by 25 percent, from 4.6 minutes to 3.4 minutes, as shown in figure 5-4.

5.3.5 New Denver International Airport (DIA)

At DIA, adding multipath exits to runways 17C and 17L increased arrival throughput by 32 percent, from 81 to 107 flights an hour. Average arrival delay with the currently used DIA schedule was decreased by 78 percent, from 14 minutes to 3.0, as shown in figure 5-5.

5.3.6 Kennedy International Airport (JFK)

At JFK (figure 5-6), the use of multipath runway exits increased the throughput of arrivals on 13R and 22L from 96 to 127 flights an hour, a 32 percent increase.

Using the current JFK schedule (which represents only about half of the theoretical throughput) yields a 28 percent improvement in arrival runway delay, decreasing it from 0.4 minutes to 0.3 minutes. At higher demand levels a greater delay saving would result.

5.3.7 Summary of Results for Multipath Runway Exits

All subject airports showed improvements in throughput and decreases in arrival runway delay when multipath exits were implemented. The results of the above-mentioned multipath exit test are summarized in figures 5-1 through 5-6. Excessive significance should not be attached to these relative results, however, since the results for each airport depend on the demand levels used for the evaluation.

PHILADELPHIA INTERNATIONAL AIRPORT

Arrival Delay

Arrival Throughput

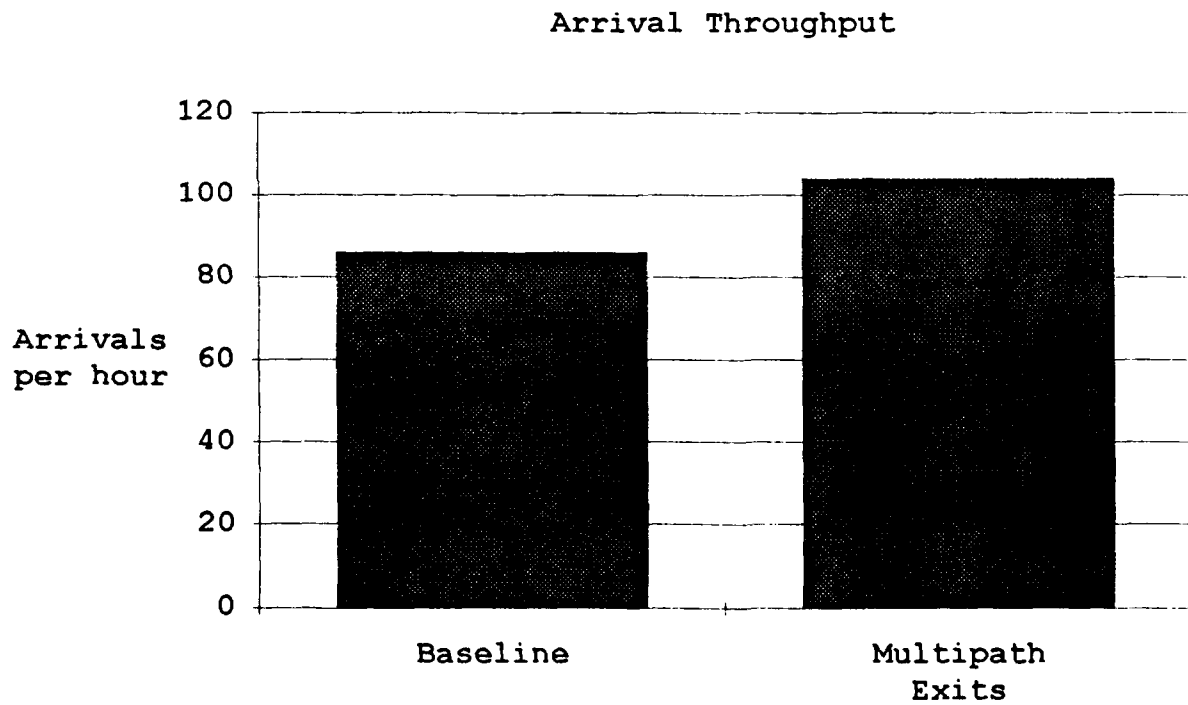Fig. 5-1   PHL Capacity Improvement Due to Multipath Runway Exits
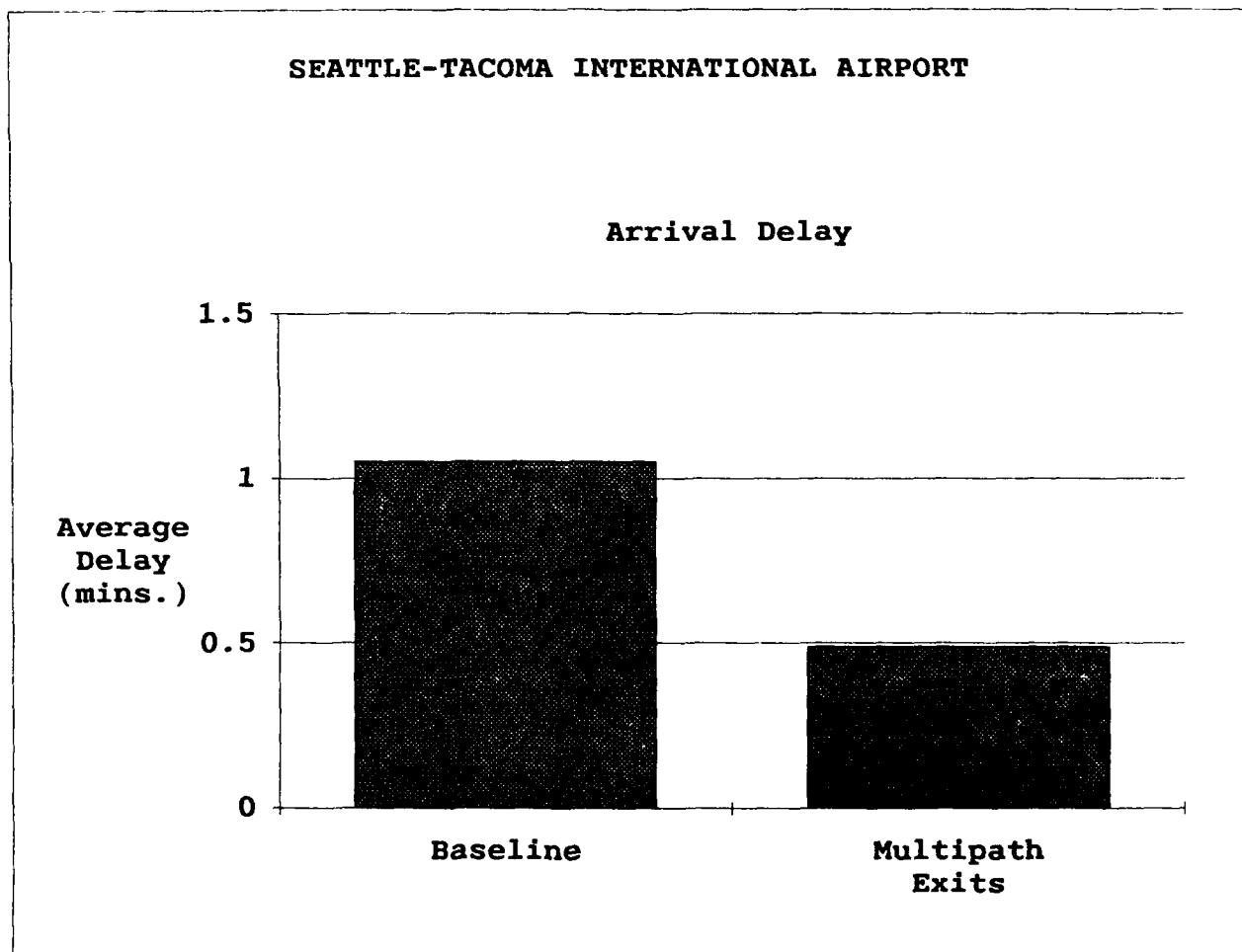
Fig. 5-2 SEA Capacity Improvement Due to Multipath Runway Exits
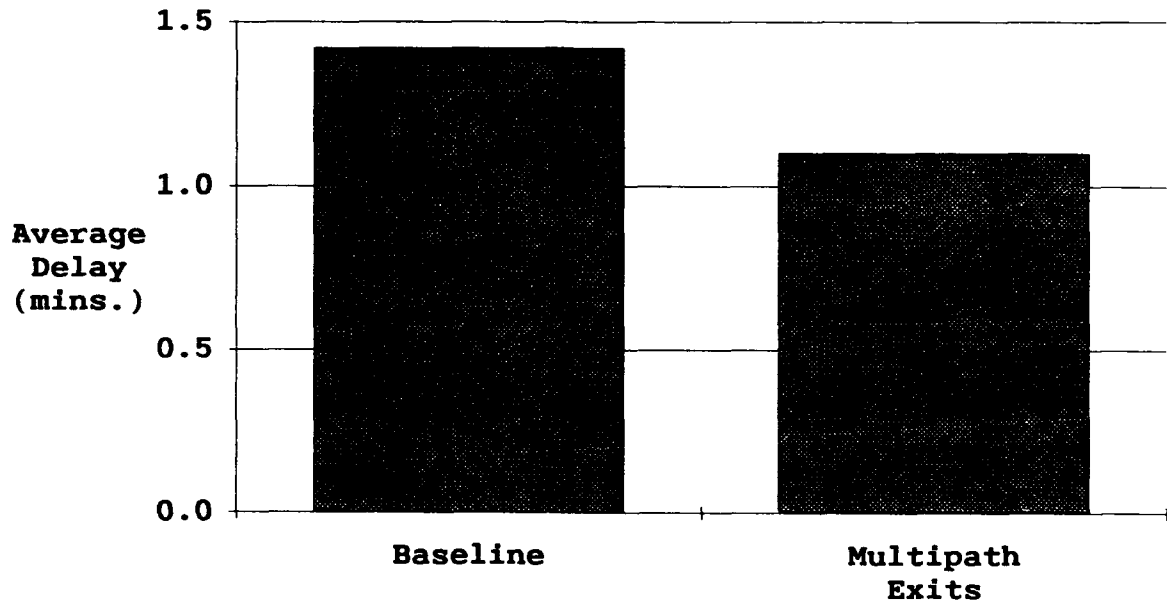
Fig. 5-3 IAD Capacity Improvement Due to Multipath Runway Exits

Fig. 5-4 DFW Capacity Improvement Due to Multipath Runway Exits

THE NEW DENVER AIPORT

Arrival Delay

Arrival Throughput
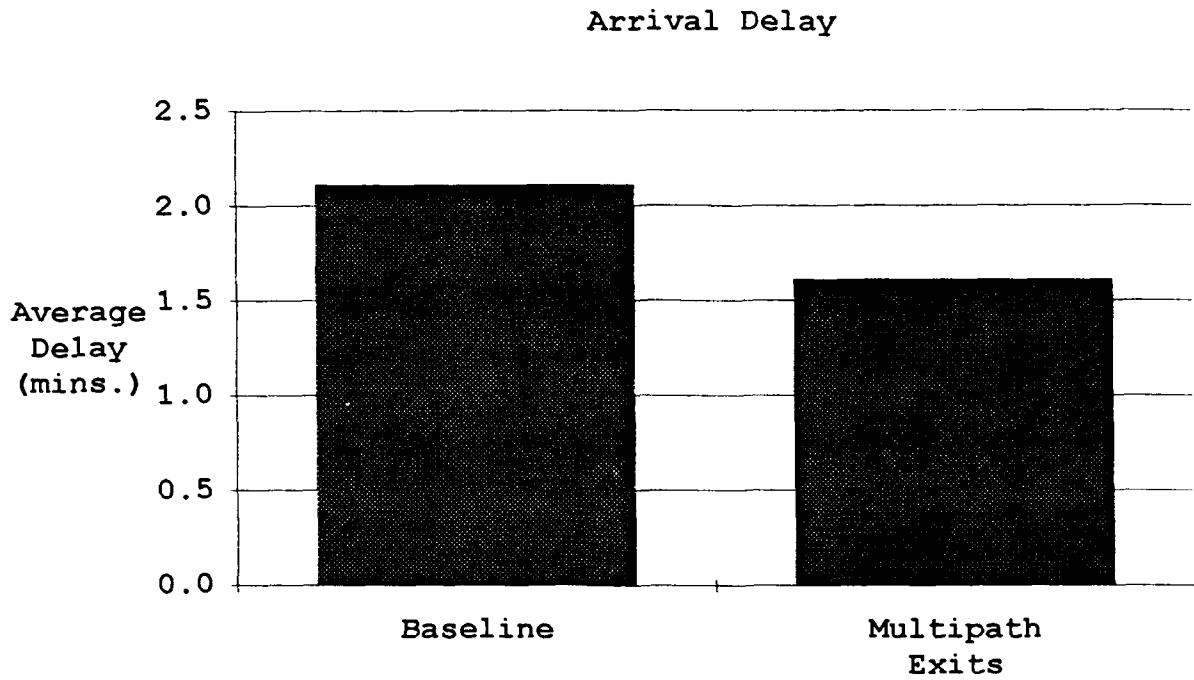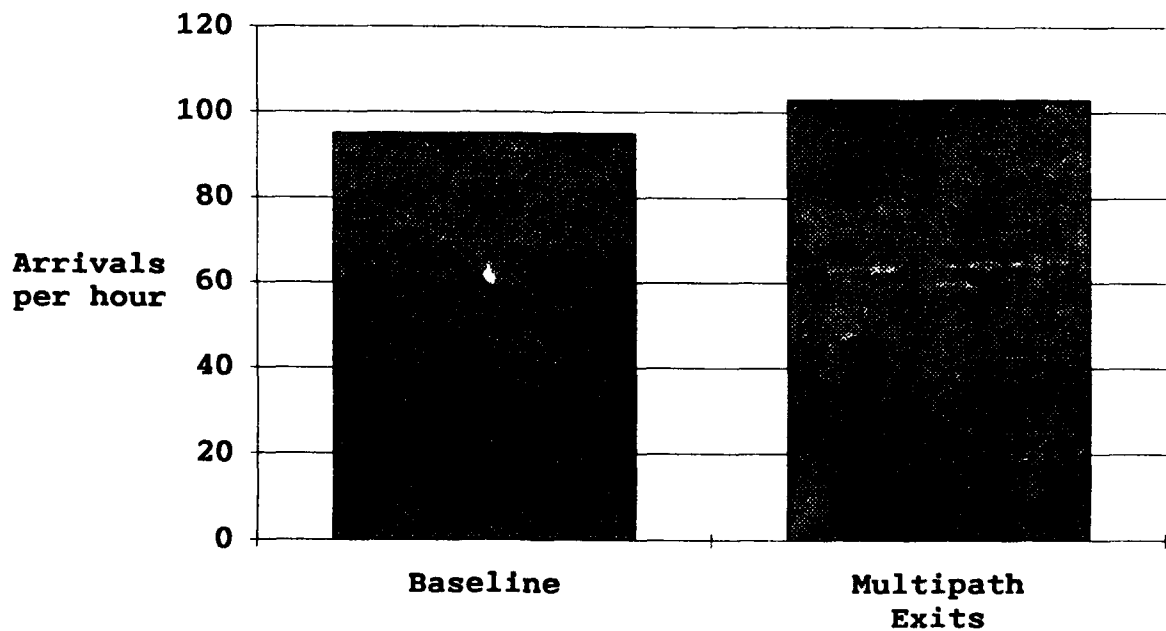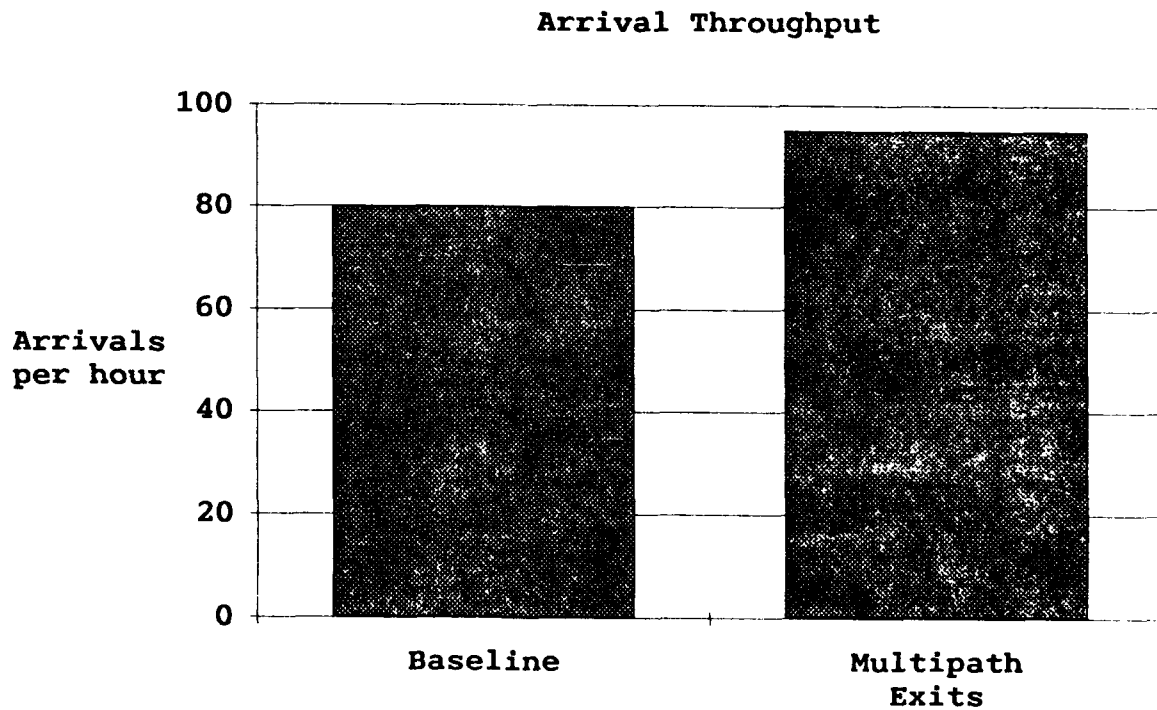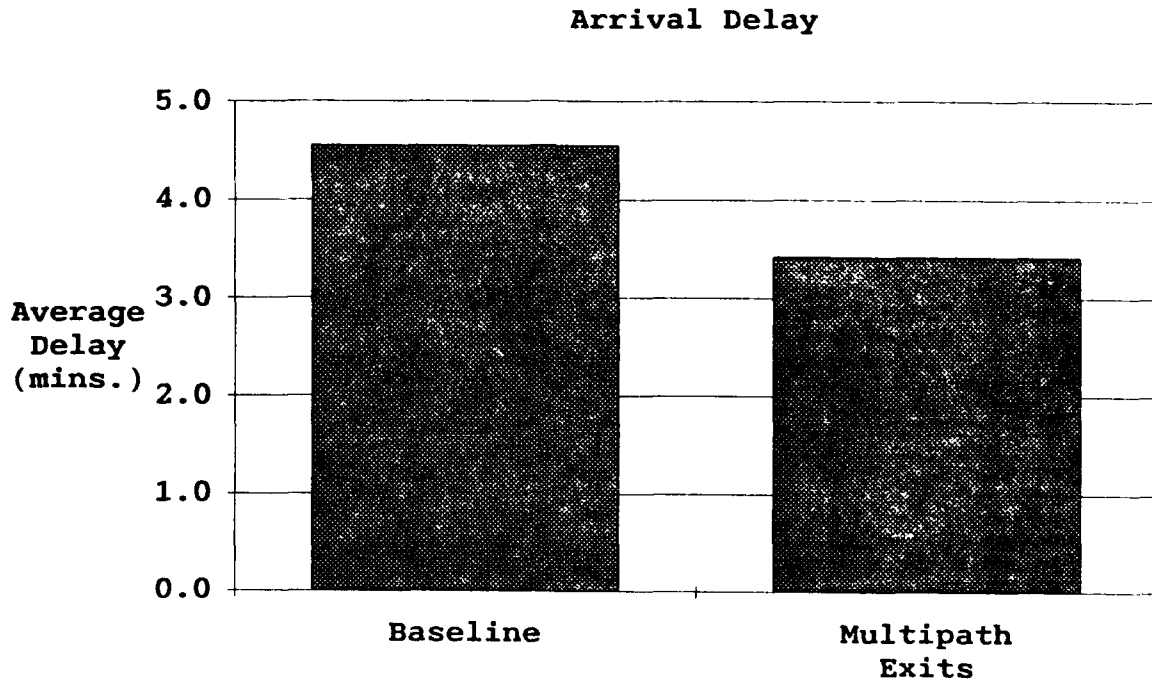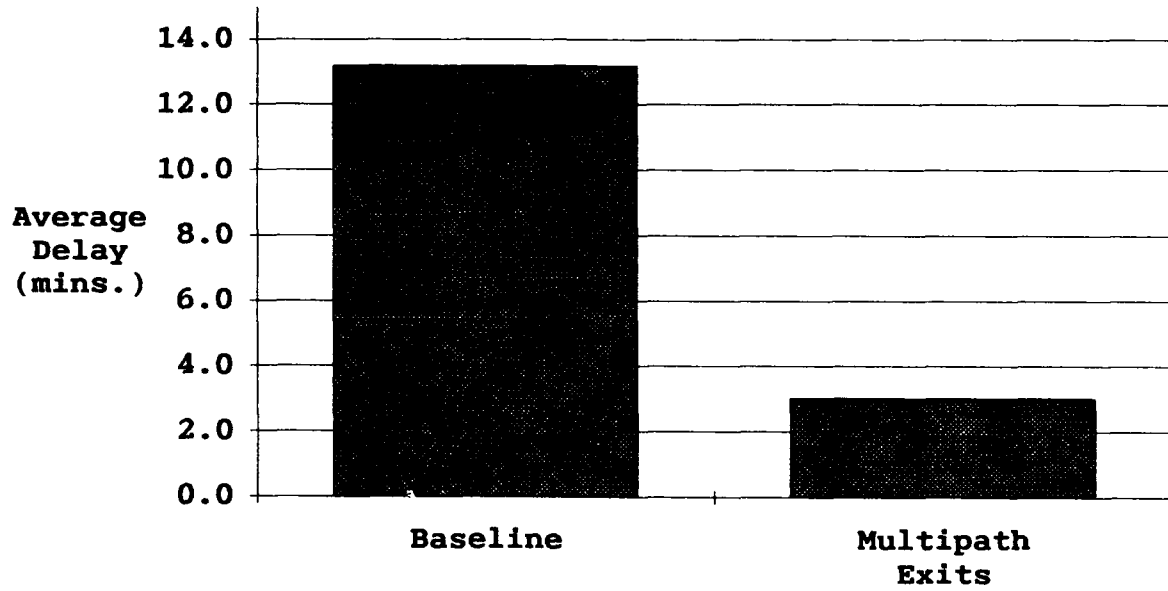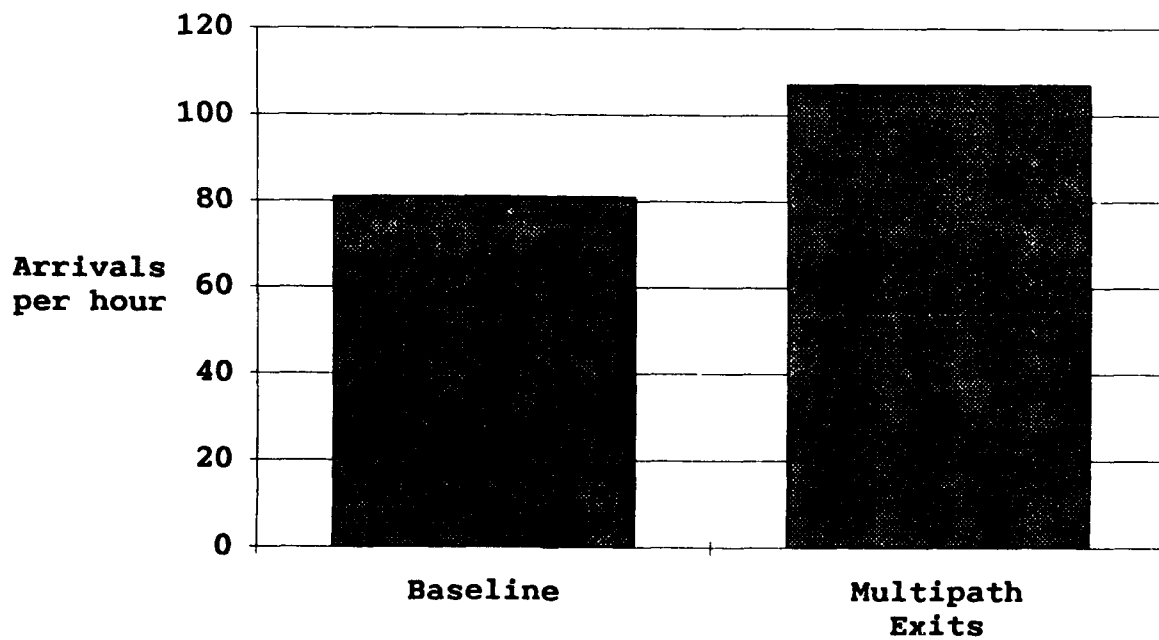

Fig. 5-5 DIA Capacity Improvement Due to Multipath Runway Exits
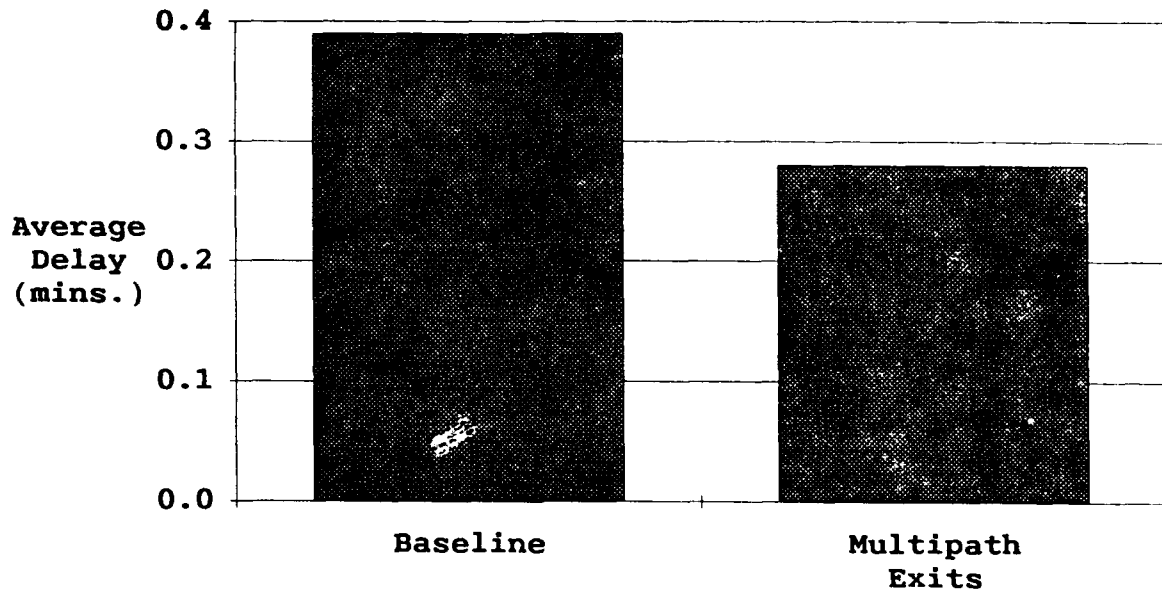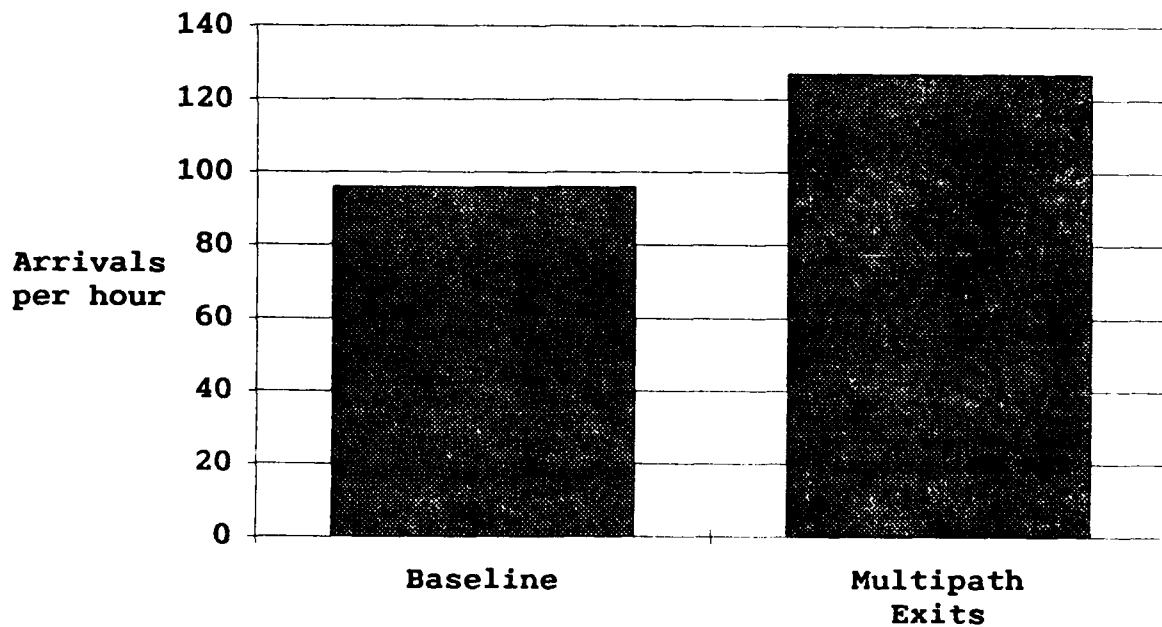
Fig. 5-6   JFK Capacity Improvement Due to Multipath Runway Exits

5.4. Capacity Sensitivity to Fleet Mix Variations

In general, larger aircraft require longer landing distances than smaller ones. Longer landing distances yield higher runway occupancy times (ROT) and therefore reduce arrival throughput. Also, all arriving aircraft following a heavy, and small aircraft following a large, require increased spacing due to wake turbulence restrictions which also reduces throughput.

For these reasons, changes in fleet mix can be expected to yield changes in the arrival throughput of an airport.

5.4.1 Sensitivity Experiments Performed

The airport configurations used for fleet mix sensitivity tests were PHL and IAD operated both with and without new multipath runway exits. Throughput simulations as described above were run for three different fleet mixes and arrival throughputs were compared. Table 5.2 shows the percentages of equipment categories for each of the three fleet mixes used for the tests.

Table 5.2 Fleet Mix Percentages

Philadelphia International Airport (PHL)

Fleet Mix	Heavy	Large	Small	Single Engine
1	4	40	46	10
2	18	26	46	10
3	18	26	36	20

Dulles International Airport (IAD)

Fleet Mix	Heavy	Large	Small	Single Engine
1	7	60	26	7
2	17	50	26	7
3	17	50	21	12

5.4.2 Analysis of Sensitivity

Arrival throughput in arrivals per hour resulting from each experiment are summarized in table 5.3.

Table 5.3 Arrival Throughput

Airport	PHL		IAD	
Multipath Runway Exits	Without	With	Without	With
Fleet Mix				
1	83	98	95	103
2	79	89	94	102
3	76	85	90	101

For the PHL sensitivity tests, the forecast 1995 fleet mix is used as fleet mix 1. Fleet mix 2 was obtained by moving 14 percent of the total from category 2 (large aircraft) to category 1 (heavy aircraft). This resulted in a 5 percent decrease in arrival throughput from 83 to 79 flights per hour for the baseline configuration and a 9 percent decrease from 98 to 89 flights per hour for the multipath runway exit configuration.

For the second sensitivity test, using fleet mix 3, 10 percent of the total flights in fleet mix 2 were changed from category 3 (small twin engine and turboprop aircraft) to category 4 (small single engine) aircraft. This yielded a 4 percent decrease in throughput from 79 to 76 flights per hour for the baseline and a 4.5 percent decrease from 89 to 85 for the multipath runway exit configuration.

For IAD fleet mix 2, 10 percent of the 1051 flights in fleet mix 1 were changed from category 2 (large aircraft) to category 1 (heavy aircraft). This resulted in a 1 percent decrease in arrival throughput from 95 to 94 flights per hour for the baseline configuration and a 1 percent decrease from 103 to 102 flights per hour for the multipath runway exit configuration. Then, 5 percent of the fleet mix 2 schedule was changed from category 3 (twin engine and turboprop) aircraft to category 4 (single engine aircraft) to create fleet mix 3. This yielded a 4.25 percent decrease in throughput from 94 to 90 flights for the baseline, and a 1 percent decrease from 102 to 101 for the multipath runway exit configuration.

Both PHL and IAD, with and without added multipath runway exits, showed decreases in arrival throughput when the percentage of either heavies or single-engine aircraft was increased. These simulation results are consistent with the anticipated effect of these changes and demonstrate how the effects of uncertainties in future demand forecasts can be evaluated using simulation.

6. Multipath Taxiways to and from Gates

This section will describe experiments that demonstrate how multipath taxiways to and from gates can alleviate potential bottlenecks that may develop as runway throughput is increased. For purposes of this study multipath taxiways are defined to be additional taxiways over and above those that would be included under current design standards.

6.1. Description of Concept

With an increase in arrival throughput resulting from use of multipath runway exits, and an increase in departure throughput due to multiple departure queues (assuming sufficient gate capacity), the capacity of taxiway routes to and from gates may become the limiting factor of overall airport capacity. The multipath taxiway concept would provide for parallel taxiway paths to accommodate the increased traffic.

Since gates are usually geometrically dispersed on the surface of an airport, it can be expected that the impact of the multipath taxiways concept will in general depend on the location of the gates. For this reason, gates are aggregated into groups on the basis of location for purposes of the evaluation.

6.2. Description of Experiments

Experiments involving multipath taxiways to and from gates were performed on two subject airports, Philadelphia International Airport (PHL) and Dulles International Airport (IAD). VMC conditions were assumed for both airports.

In order to study the multipath taxiways concept, two simulations were run for each airport, one with and one without the multipath taxiways; resulting delays were then compared. In each case, multipath runway exits added for the previous task were used to increase throughput so as to sufficiently exercise the subject taxiways. In addition, multipath runway exits were added to all IAD arrival runways and all runways were utilized at full capacity. Also, new high demand schedules were created using the Airport Machine Schedule Generator. For purposes of analyzing the contribution to delay by specific gate groups, airlines were assigned on the basis of gate location. Thus delays and times reported in The Airport Machine's output report, which are categorized by airline, can be used to compare delay on the basis of gate group.

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6.2.1. PHL Experiments

For PHL, the inner runway was relocated laterally to make room for an additional parallel taxiway between the runway and the gates. The second inner taxiway was also continued around in front of the north end terminals, AE and AD. These taxiway additions are needed to alleviate congestion in the terminal area and increase taxiway throughput. To ensure sufficient gate capacity, two fingers were added at the east and west ends of the existing terminal complex1. Each terminal finger was assumed to be occupied by a different airline as illustrated in figure 6-1, which shows the runway relocation and added parallel taxiway geometry, as well as the runway operational direction used for these experiments. The two-letter airline names denote the name of the (fictitious) airline occupying the particular finger. These airlines were assigned to three gate groups in accordance with table 6.1.

Table 6.1 PHL Airline - Gate Group Assignments

Gate Group	Associated Airlines
1	AP, AA, AB
2	AC, AD
3	AE, AF

Figure 6-2 shows PHL taxiway geometry as it presently exists without the added parallel taxiway but with multiple runway exits.

6.2.2. IAD Experiments

For IAD, a proposed future taxiway geometry that incorporates multipath taxiways to gates is shown in figure 6-3. This alternative features four east/west through taxiways, in addition to the six east/west taxiways used for pushback from gates. Figure 6-4 illustrates the alternative that does not include the through taxiways.

Simulations were performed with and without these four through taxiways. Again, one airline was assigned to each terminal so as to enable gate group contribution comparisons. The two alphanumeric character names in figure 6-3 represent the airlines occupying each terminal. The first (numeric) character denotes the gate group and the second (alpha) character denotes the east or west side of the terminal area. Figure 6-3 also shows the runway configuration used.

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[1] This runway, taxiway, and gate relocation scheme is one of several possible future capacity improvement alternatives being considered by the city of Philadelphia for the airport.

Fig. 6-1 PHL with Multipath Taxiways to/from Gates
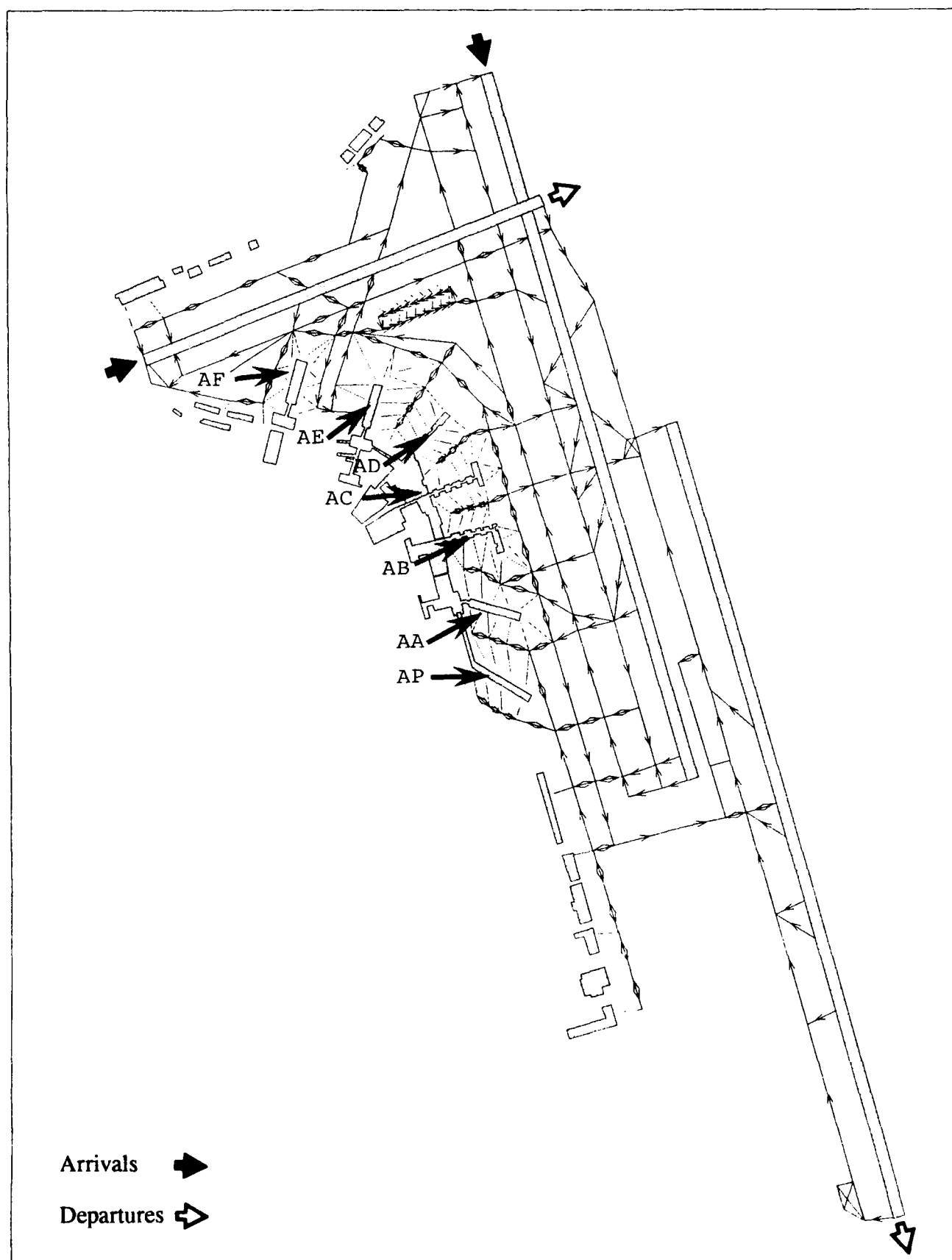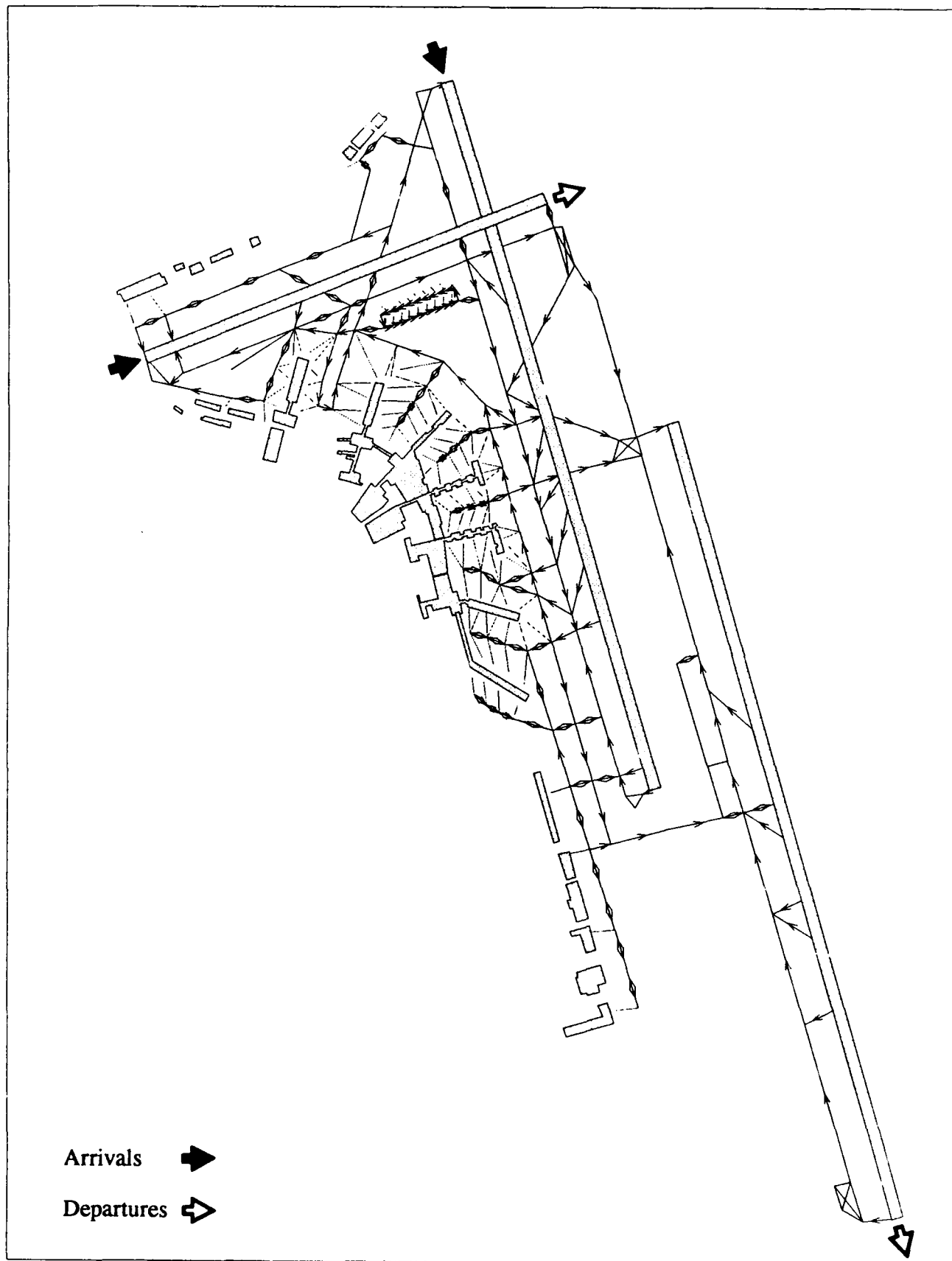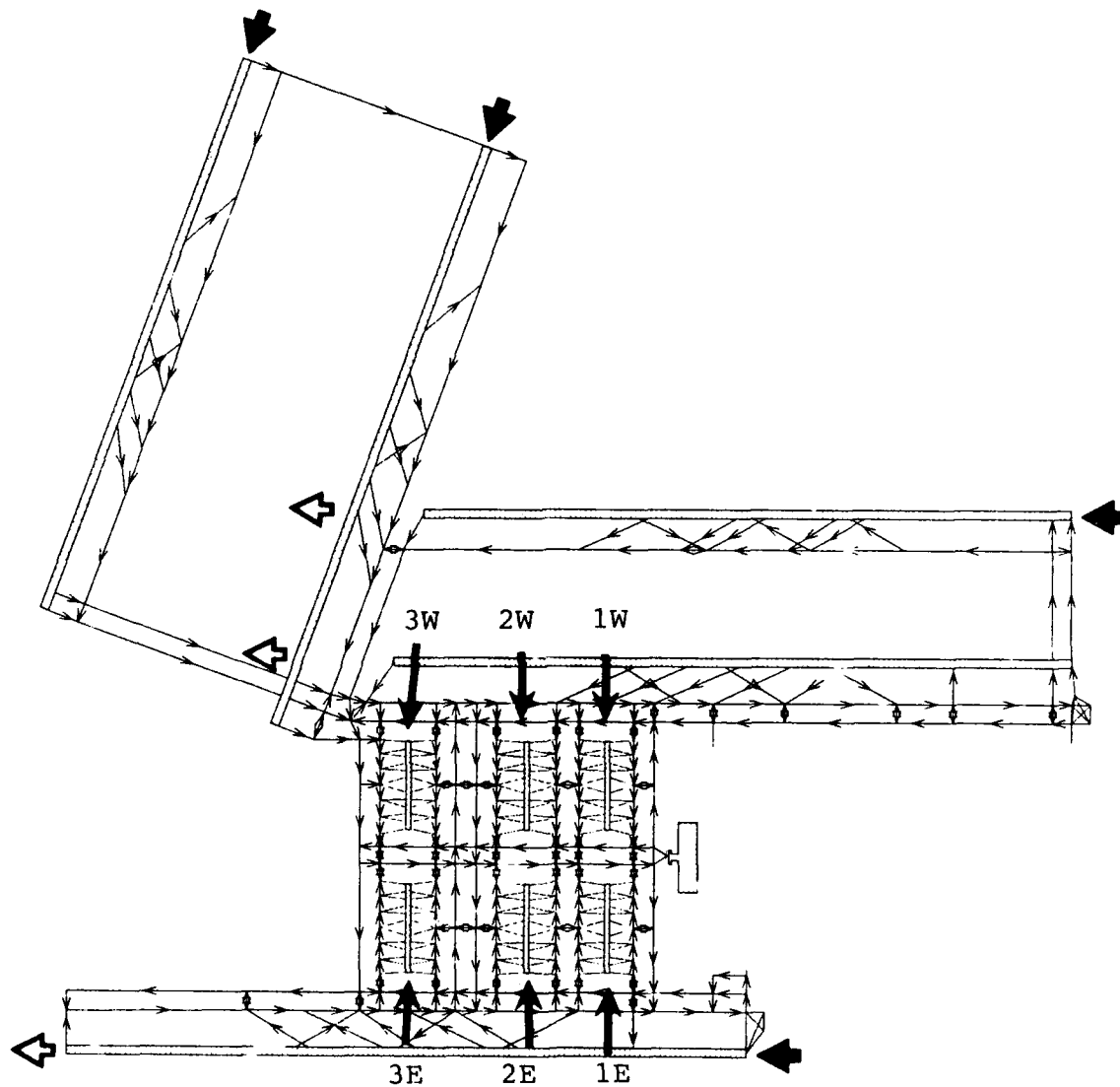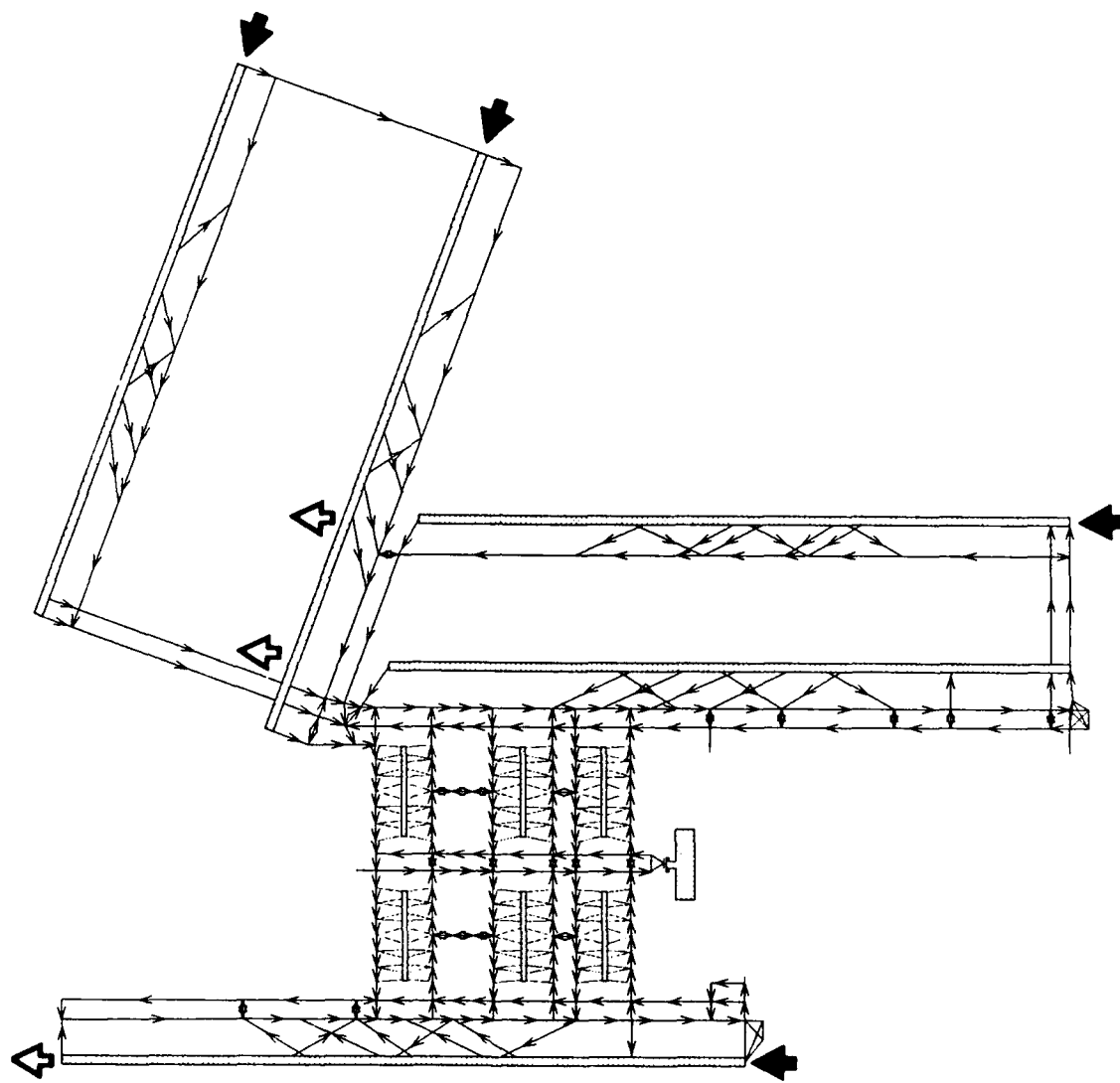
44

Arrivals ➤

Departures ⇨

Fig. 6-2 PHL without Multipath Taxiways to/from Gates

45

Fig. 6-3 IAD with Multipath Taxiways to/from Gates

Arrivals ➡

Departures ⇨

Fig. 6-4 IAD without Multipath Taxiways to/from Gates

6.3. Analysis of Results

The results of the above experiments for both PHL and IAD show that significant reductions of 10 to 15 percent in overall time and delay of aircraft operations can be achieved by application of the proposed multipath taxiway concept. These results are detailed below.

6.3.1. PHL Results

Table 6.2 summarizes the average time and delay results for the two PHL configurations with and without the added parallel taxiway. Figures 6-5 and 6-6 show where these delays occur on the taxiway system. The areas of the shaded circles are proportional to the delay absorbed at the intersection located at the center of the circle.

Table 6.2 PHL Average Delay/Time (minutes)

Multipath Taxiways to Gates		Without	With	% Improvement
Taxi In	Time	3.9	4.1	-5%
	Delay	1.7	0.6	65%
	Runway Crossing Delay	0.1	0.1	0%
	Total	5.7	4.8	16%
Arrival Runway Delay		7.0	5.6	20%
Arrival Total		12.7	10.4	18%
Taxi Out	Time	6.5	6.5	0%
	Delay	1.1	0.5	55%
	Runway Crossing Delay	1.4	1.4	0%
	Total	9.0	8.4	7%
Departure Runway Delay		11.7	11.1	5%
Departure Total		20.7	19.5	6%
Arrival and Departure Total		33.4	29.9	10%

48
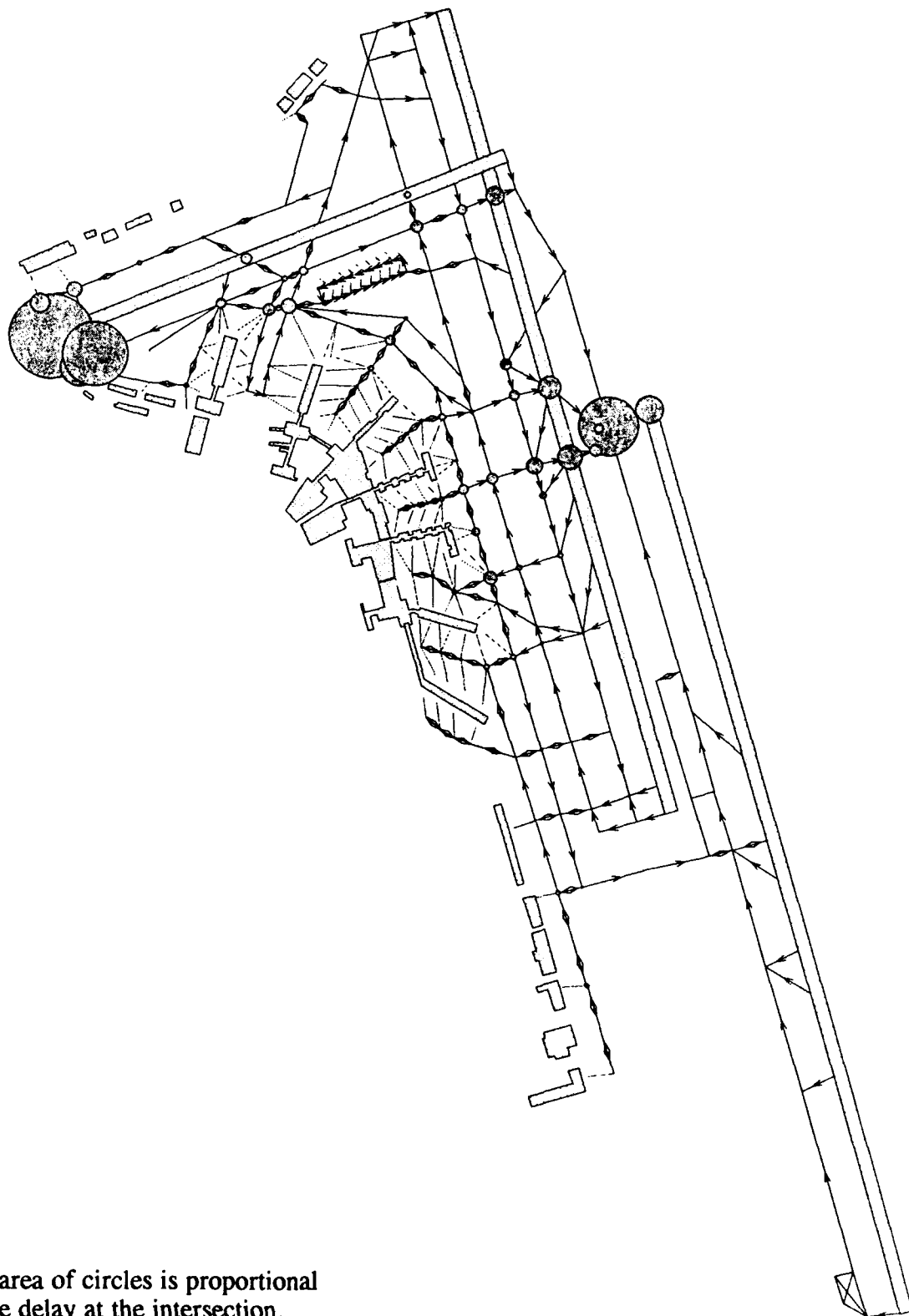
The area of circles is proportional
to the delay at the intersection.

Fig. 6-5   PHL Runway and Taxiway Delay with Multiple Taxiways
to/from Gates

49

The area of circles is proportional
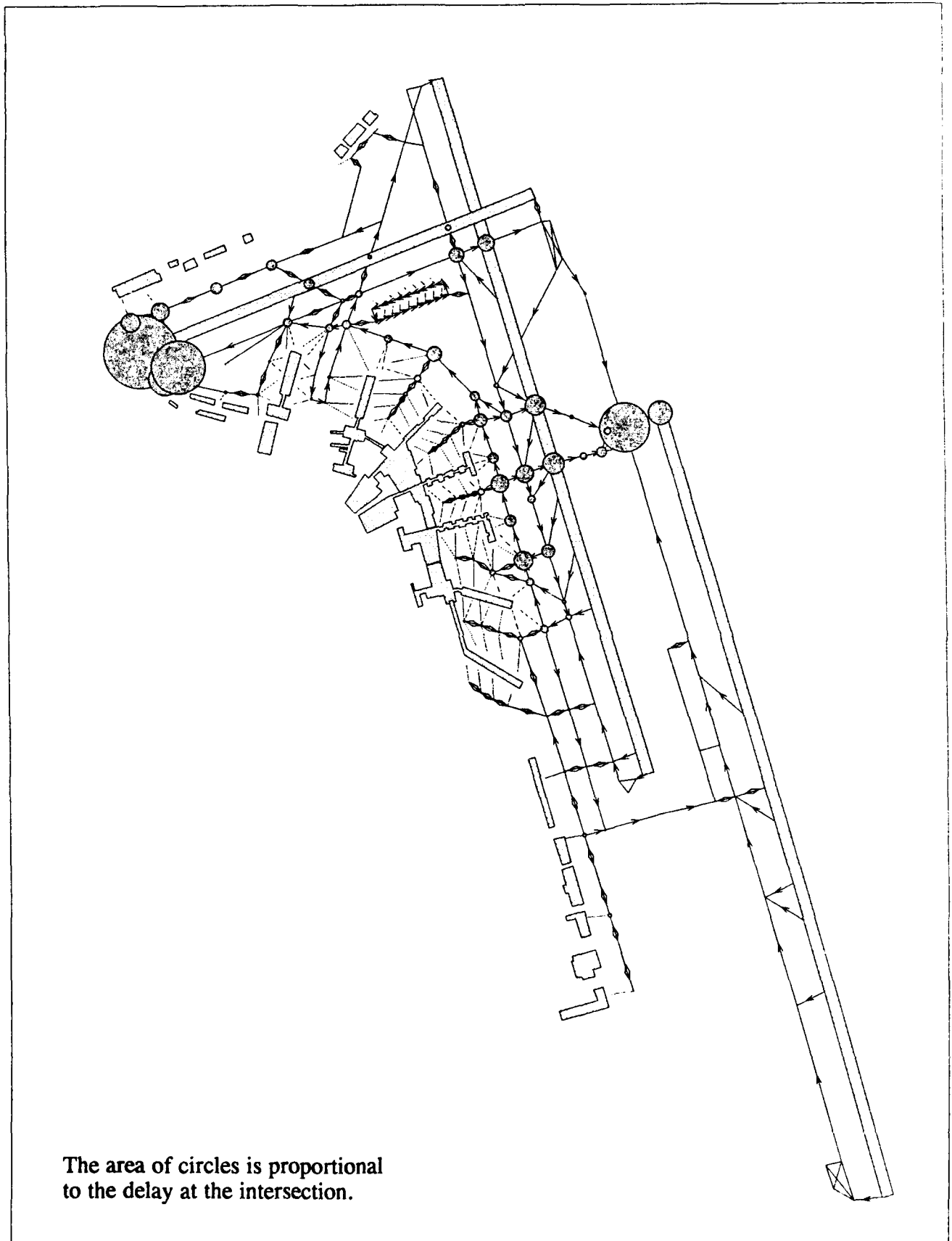to the delay at the intersection.

Fig. 6-6 PHL Runway and Taxiway Delay without Multiple Taxiways
to/from Gates

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Although large percentage decreases occur in taxi-in and taxi-out delays, these decreases are partially offset by a slightly increased taxi-in time, yielding a net overall decrease in delay and time of 10 percent when multipath taxiways are added at PHL.

Analysis of the contribution of delay and time by gate group for configurations with and without multipath taxiways to and from gates is presented in table 6.3. This table shows, while the gate groups nearest the runway exits used have less taxi time and delay, the effects average out when both arrival and departure results are summed.

Table 6.3 PHL Gate Group Time and Delay Contributions (minutes)

Multipath Taxiways to Gates		Without			With		
Group		1	2	3	1	2	3
Runway Delay	Arrival	7.9	7.4	8.4	6.3	6.1	6.6
	Departure	8.9	8.9	7.3	7.6	8.1	6.3
Taxi In	Time	2.9	3.9	4.4	3.2	4.0	4.6
	Delay	1.6	2.3	2.0	0.5	0.8	0.6
	Runway Crossing Delay	0.0	0.0	0.0	0.0	0.0	0.0
Taxi Out	Time	7.1	5.6	7.2	7.0	5.5	7.2
	Delay	0.9	0.5	0.9	0.4	0.4	0.4
	Runway Crossing Delay	1.8	2.3	1.1	1.7	2.1	1.0
Arrival and Departure Total		31.1	30.8	31.2	26.8	27.0	26.8
Overall Average		31.0			26.8		

6.3.2. IAD Results

Table 6.4 summarizes the results obtained for IAD configurations with and without the added parallel taxiway, and figures 6-7 and 6-8 show where taxiway/crossing delays occur.

Table 6.4 IAD Average Delay/Time (minutes)

Multipath Taxiways to Gates		Without	With	% Improvement
Taxi In	Time	9.6	8.9	7%
	Delay	1.7	0.4	76%
	Runway Crossing Delay	0.6	0.5	17%
	Total	11.9	9.8	18%
Arrival Runway Delay		0.4	0.4	0%
Arrival Total		12.3	10.2	17%
Taxi Out	Time	11.9	11.1	7%
	Delay	2.4	1.1	54%
	Runway Crossing Delay	0.9	0.8	11%
	Total	15.2	13.0	14%
Departure Runway Delay		2.0	1.8	10%
Departure Total		17.2	14.8	14%
Arrival and Departure Total		29.5	25.0	15%

With the subject multipath taxiways employed at IAD, both taxi time and taxi delay were decreased.

Contribution of delay and time by gate group for configurations with and without multipath taxiways to and from gates is summarized in table 6.5.

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The area of circles is proportional
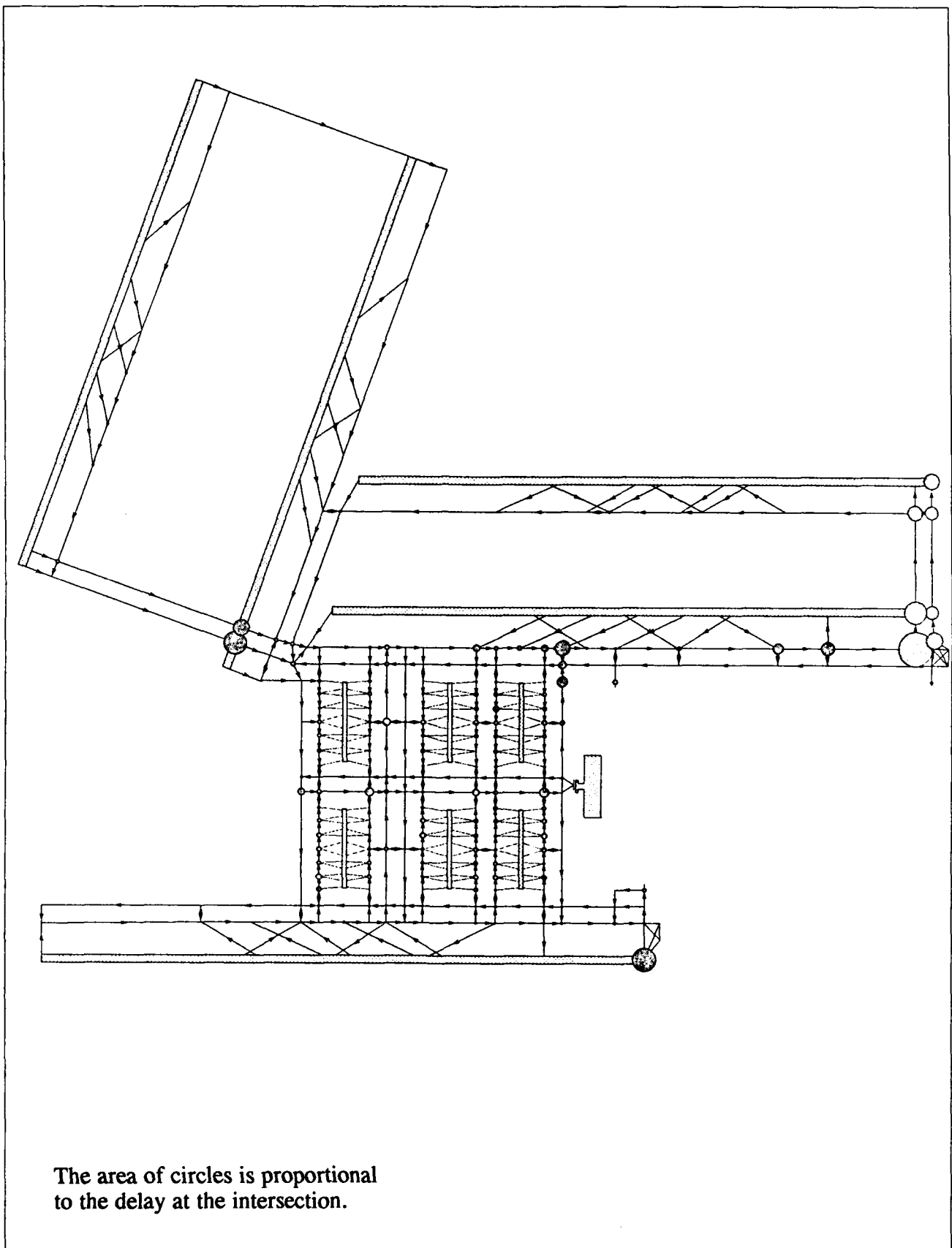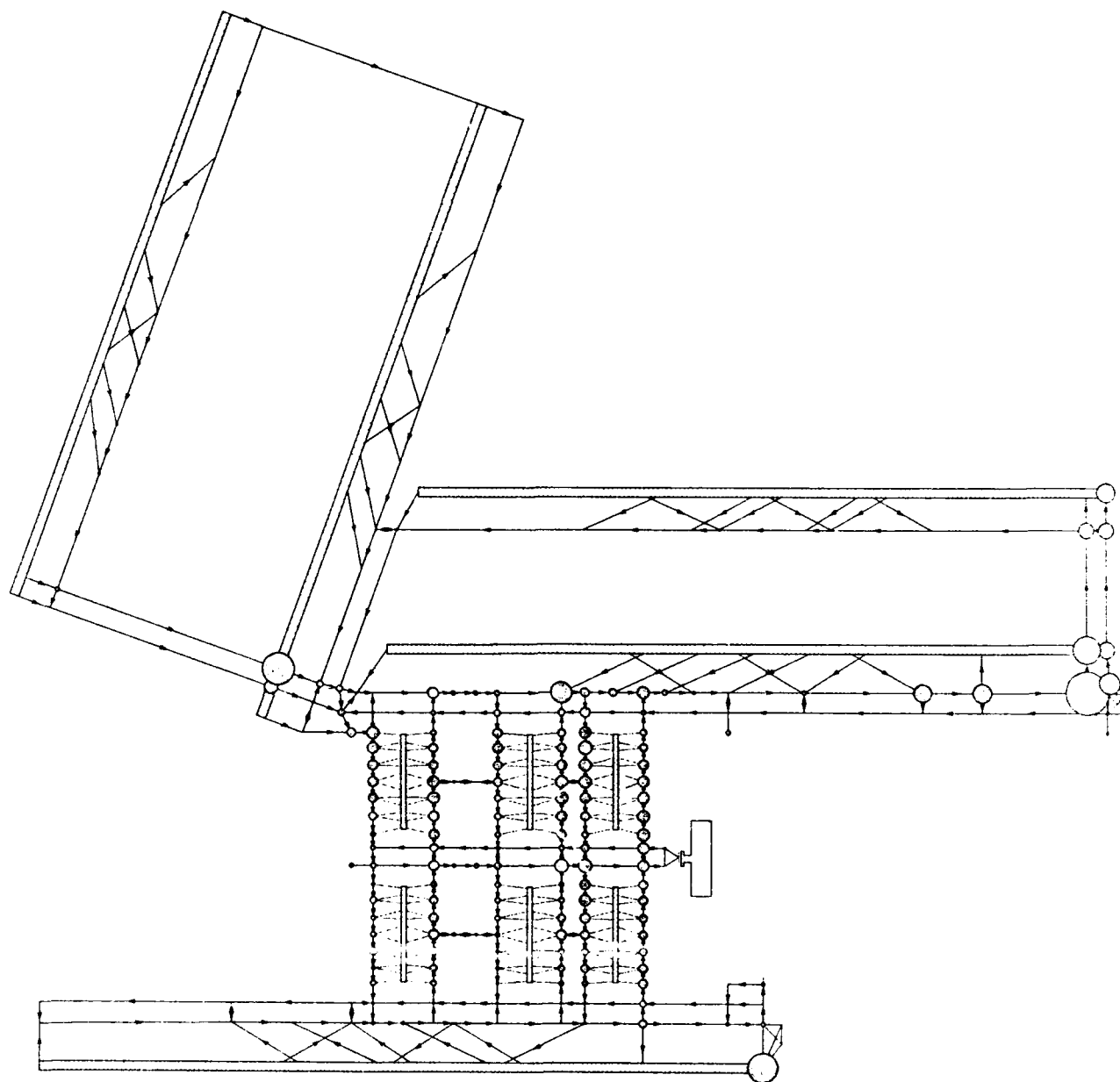to the delay at the intersection.

Fig. 6-7 IAD Runway and Taxiway Delay with Multiple Taxiways
to/from Gates

53

The area of circles is proportional
to the delay at the intersection.

Fig. 6-8   IAD Runway and Taxiway Delay without Multiple Taxiways
to/from Gates

54

Table 6.5 IAD Gate Group Time and Delay Contributions (minutes)

Multipath Taxiways to Gates		Without			With		
Group		1	2	3	1	2	3
Runway Delay	Arrival	0.4	0.4	0.4	0.4	0.4	0.4
	Departure	2.0	2.2	2.0	1.8	1.9	1.9
Taxi In	Time	10.2	9.5	8.3	9.4	8.7	7.6
	Delay	2.1	1.4	1.6	0.5	0.5	0.4
	Runway Crossing Delay	0.6	0.7	0.4	0.5	0.5	0.5
Taxi Out	Time	11.1	12.1	13.5	10.4	11.3	12.5
	Delay	2.4	2.5	2.5	1.2	1.1	1.1
	Runway Crossing Delay	0.9	0.9	1.0	0.8	0.8	0.8
Arrival and Departure Total		29.8	29.6	29.6	24.9	25.2	25.1
Overall Average		29.7			25.1		

7. Sensitivity to Exit and Taxiway Geometry

This section of the report will describe the use of the simulation to demonstrate and evaluate the sensitivity of runway and taxiway delay to specific geometric features of the exit and taxiway system, such as dual lane taxiways and exit radius.

7.1 Dual Lane Taxiways

Dual lane taxiways are taxiways having sufficient width that two aircraft can pass in opposite directions. Some dual lane taxiways may have sufficient width to accommodate only aircraft having less than specified wingspans. These restrictions are modeled in The Airport Machine by assigning an effective width to each taxiway segment and an effective wingspan to each aircraft equipment category. The model will then permit passing only of flights for which the sum of the wingspans is less than the taxiway width. For the purpose of these experiments all aircraft were considered capable of passing on the designated taxiway segments, with the exception of two category 1 (heavy) aircraft.

In order to illustrate the effects of dual lane taxiways, simulation experiments were performed for configurations of PHL with and without simultaneous bidirectional taxiway traffic in three selected locations. Figure 7-1 shows PHL with the proposed dual lane taxiways marked, and the location of taxiway and runway crossing delay shown. The corresponding taxiway and runway crossing delay diagram without dual lane taxiways is shown in figure 6-5.

Widening of the two cross-taxiways between the terminal area and runway 9L-27R permits arrivals that land short on runway 27R to taxi in to the terminal area directly, instead of having to taxi west to the first northbound cross taxiway and then taxi back east to the eastern terminal fingers. The widening of the taxiway parallel to runway 17/35 permits runway 17 departures to queue on the east side of runway 17/35 without interfering with international flights taxiing out of their gates to depart on runway 27L.

Table 7.1, which summarizes results of the above simulations, shows a 19 percent reduction in overall time and delay.
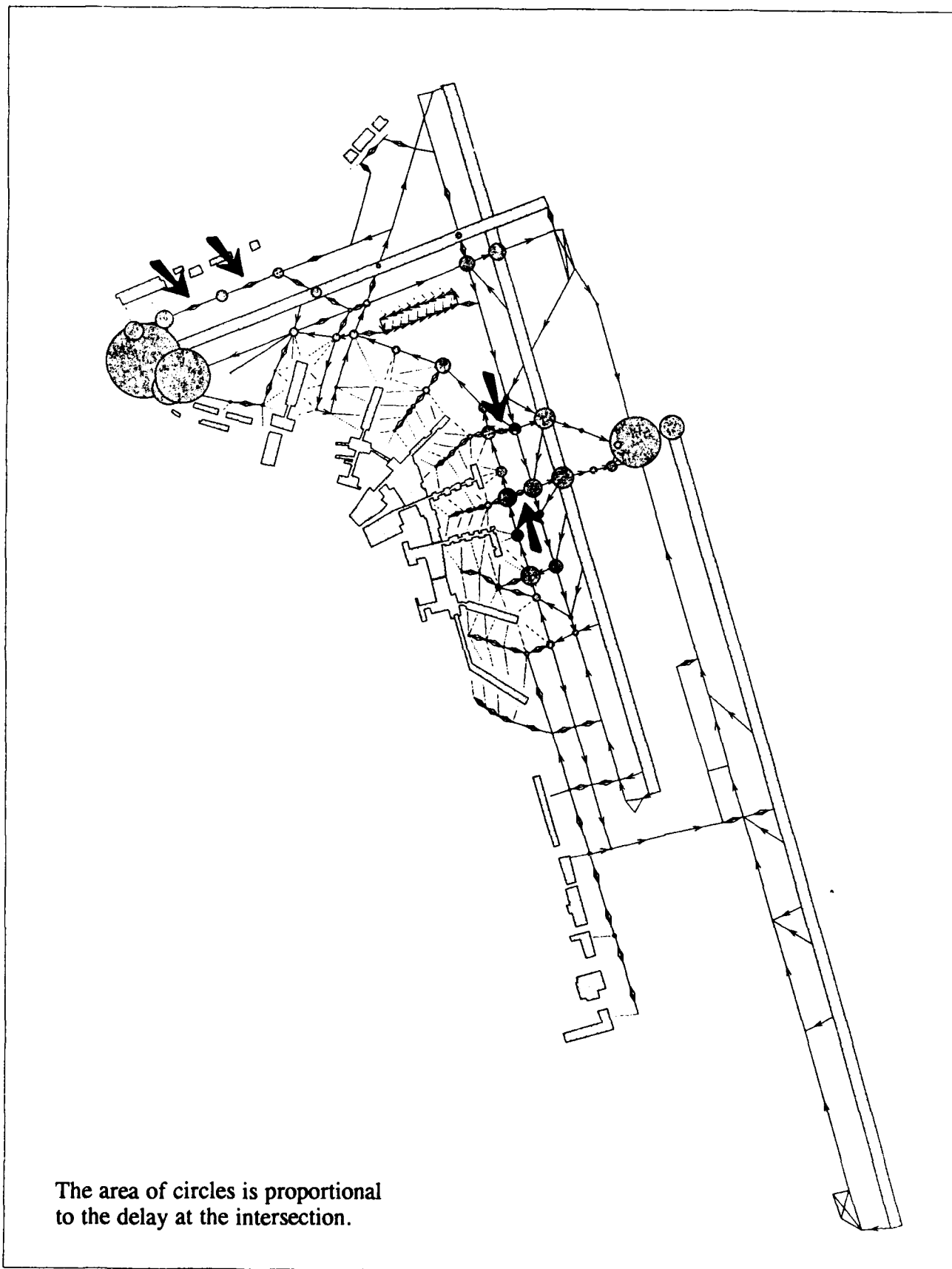
56

The area of circles is proportional
to the delay at the intersection.

Fig. 7-1 PHL Runway and Taxiway Delay with Dual Lane Taxiways

Table 7.1 PHL Delay Reduction for Dual Lane Taxiways (minutes)

Dual Lane Taxiways		Without	With	% Improvement
Taxi In	Time	3.9	3.5	10%
	Delay	1.7	0.7	59%
	Runway Crossing Delay	0.1	0.1	0%
	Total	5.7	4.3	25%
Arrival Runway Delay		7.0	4.2	40%
Arrival Total		12.7	8.5	33%
Taxi Out	Time	6.5	6.5	0%
	Delay	1.1	0.7	36%
	Runway Crossing Delay	1.4	1.3	7%
	Total	9.0	8.5	6%
Departure Runway Delay		11.7	10.0	15%
Departure Total		20.7	18.5	11%
Arrival and Departure Total		33.4	27.0	19%

7.2 Exit Radii and Additional Fillets

By decreasing exit radii and adding fillets to existing exits, runway exit speeds can be increased without affecting safety. The Airport Machine simulation model summarizes the effects of exit taxiway angle and radius of fillets in terms of maximum exit speed feasible for each category of aircraft. When a simulation run is started, the runway occupancy times (ROTs) and best-case exit probabilities are computed and written out to the simulation ECHO file. To illustrate the effects of the exit geometry, the PHL database was modified to permit exit speeds 10 knots higher than previously used values. The Airport Machine model was then used to calculate best-case exit probabilities and mean ROTs for both of these idealized cases.

Table 7.2 shows the two sets of exit speeds used.

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Table 7.2 PHL Exit Speeds Arrays (knots)

EC	Current				Potential			
	H	N	R	A	H	N	R	A
Heavy	50	40	10	0	60	50	20	10
Large	45	35	12	0	55	45	22	10
Small	35	30	15	10	45	40	25	20
Single Engine	35	30	15	10	45	40	25	20

H= high speed exit

N= normal angled exit

R= right angled exit

A= acute (reverse) angled exit

Tables 7.3 through 7.6 show the cumulative exit probabilities and mean ROT values for PHL runways 27R and 17 for both current and potential exit speed arrays.

Table 7.3

Current Cumulative Exit Probabilities and Mean ROTs for PHL Runway 27R (seconds)

Runway 27R			Cumulative Probability By Equipment Category				Mean ROT By Equipment Category			
Exit	Node	Dist	1	2	3	4	1	2	3	4
1	22	0	0	0	0	0	*	*	*	*
2	21	1843	0	0	0	0	*	*	*	*
3	20	2215	0	0	0	50	*	*	*	27
4	18	3623	0	37	100	100	*	25	30	41
5	16	4406	77	100	100	100	28	30	35	50
6	15	5195	100	100	100	100	33	36	43	61
7	14	5498	100	100	100	100	34	38	46	65
8	23	6238	100	100	100	100	41	46	54	75
9	13	7112	100	100	100	100	54	58	66	90
10	12	9055	100	100	100	100	71	77	86	116
11	11	9357	100	100	100	100	74	80	89	121

Table 7.4

Potential Cumulative Exit Probabilities and Mean ROTs for PHL Runway 27R
(seconds)

Runway 27R			Cumulative Probability By Equipment Category				Mean ROT By Equipment Category			
Exit	Node	Dist	1	2	3	4	1	2	3	4
1	22	0	0	0	0	0	*	*	*	*
2	21	1843	0	0	0	0	*	*	*	*
3	20	2215	0	0	0	66	*	*	*	25
4	18	3623	22	59	100	100	22	24	29	41
5	16	4406	98	100	100	100	27	29	34	50
6	15	5195	100	100	100	100	31	35	42	60
7	14	5498	100	100	100	100	34	38	45	65
8	23	6238	100	100	100	100	41	45	53	75
9	13	7112	100	100	100	100	52	56	64	88
10	12	9055	100	100	100	100	69	75	84	115
11	11	9357	100	100	100	100	72	78	87	119

Table 7.5

Current Cumulative Exit Probabilities and Mean ROTs for PHL Runway 17 (seconds)

Runway 17			Cumulative Probability By Equipment Category				Mean ROT By Equipment Category			
Exit	Node	Dist	1	2	3	4	1	2	3	4
1	56	0	0	0	0	0	*	*	*	*
2	55	390	0	0	0	0	*	*	*	*
3	54	2136	0	0	0	32	*	*	*	27
4	53	2324	0	0	0	100	*	*	*	23
5	52	3174	0	0	75	100	*	*	26	33
6	51	4257	14	64	100	100	34	35	37	51
7	21	4671	0	0	0	0	*	*	*	*
8	50	5432	0	0	0	0	*	*	*	*

Table 7.6

Potential Cumulative Exit Probabilities and Mean ROTs for PHL Runway 17 (seconds)

Runway 17			Cumulative Probability By Equipment Category				Mean ROT By Equipment Category			
Exit	Node	Dist	1	2	3	4	1	2	3	4
1	56	0	0	0	0	0	*	*	*	*
2	55	390	0	0	0	0	*	*	*	*
3	54	2136	0	0	0	45	*	*	*	25
4	53	2324	0	0	0	100	*	*	*	23
5	52	3174	0	10	93	100	*	21	25	33
6	51	4257	20	72	100	100	32	33	35	49
7	21	4671	0	0	0	0	*	*	*	*
8	50	5432	0	0	0	0	*	*	*	*

Increasing exit speed is shown to both increase the percent-use and to decrease the ideal occupancy times of some exits. The overall effect is to reduce the mean ROT for runway 27R from 28.3 seconds to 26.0 second, an eight percent reduction. For runway 17 the reduction is only two percent, from 25.9 seconds to 25.4 seconds.

8. Conclusions

The detailed results of each of the multipath concepts are provided in the 'analysis of results' subsection.

In general, these results show that the application of each concept and the level of benefits provided depend heavily on the specifics of the individual airports:

- The benefits provided by multiple taxiway/runway crossings depend both on the rate at which flights must cross the runway (going to/from another runway) and the frequency and duration of naturally occurring gaps in the arrival/departure stream of the runway.

- The benefits of using multiple departure queues depend on the number of airspace routes available for the departures, the distribution of flights over those routes, and the nature of the in-trail restrictions likely to be encountered.

- The benefits provided by multipath runway exits depend on the congestion on adjacent taxiways, which could impede egress from the exits.

- Likewise, the benefits of multipath taxiways to and from gates depend first on the availability of space for the additional taxiways, and secondly on the compatibility of the terminal/gates layout.

For each multipath concepts, the six selected airports provided candidates for which the concept would significantly resolve future ground traffic congestion problems.

In addition to demonstrating these airport design concepts, the study has also shown how simulation techniques can be used effectively to provide quantitative evaluations of airport improvement alternatives. Using such tools will help personnel plan for future airport needs.

Appendix A

Description of The Airport Machine Simulation Model

The airport simulation model used on this project is called The Airport Machine. The Airport Machine is a general purpose airport simulation that has been designed for use at any airport without the need for program changes. Data input to the program describes the airfield layout, air traffic control rules and procedures, and aircraft performance characteristics.

Actual schedules may be used to drive the model, or a separate schedule generator program can be used to generate random schedules in accordance with a prescribed hourly arrival/departure rate and aircraft mix.

The Airport Machine is implemented in a desk-top computer and uses a high resolution color graphic terminal to display the operation of the simulation in animated graphic form, and to permit the user to interact with the simulation as it progresses.

This interactive desk-top implementation has been designed to reduce the start-up costs and delays that have limited the application of simulations in the past and to enhance the accessibility of this valuable tool to analysts and planners.

The data bases for one or more airports can be assembled and stored on disk so they are instantly available for use in reviewing and analyzing operational or planning problems as the needs arise.

Assembly of the data base is facilitated by an ancillary program that makes extensive use of interactive computer graphics to edit geometry related data such as taxiway geometry and directions. Taxiway routings can also be edited interactively while running the simulation itself.

Special capabilities of The Airport Machine that are of particular importance to the subject investigations include:

- detailed landing deceleration modeling

- deceleration and exit selection sensitivity to runway exit geometry and location

- controlled queuing of departures and adaptive selection of the next flight to depart

- adaptive spacing of arrivals to permit runway crossings

- user interaction to permit optimization of operations

The versatility and integrity of The Airport Machine have been demonstrated by the ability of others, not involved in its development, to use this tool effectively. Valuable feedback from users, gained through applications at a variety of U.S and foreign airports, has helped to enhance operation of the model. The design of the model is not frozen but is continually being enhanced by improvements based on user experience and the demands of new applications.

Current licensees of the model include:

- U.S. DOT Federal Aviation Administration for 12 regional offices and supporting agencies such as:

    FAA Technical Center

    Transportation Systems Center

    Mitre Corporation.

- Transport Canada (for use at all Canadian Airports)

- Dallas/Ft. Worth International Airport Board

- British Civil Aviation Authority (Heathrow)

- Amsterdam Airport Authority (Schiphol)

- Flughafen Frankfurt/Main AG

- Baltimore/Washington International Airport

- Civil Aviation Administration of Sweden for all Stockholm airports

- City and County of Denver for the New Denver Airport

- City and County of Denver for Stapleton International Airport

- Port of Seattle for Sea-Tac International Airport and Boeing Field

- Aeroports de Paris for Charles de Gaulle Airport

- Norwegian Civil Aviation Administration for the New Oslo Airport and other Norwegian airports

- Republic of Singapore CAA for Changi International Airport

Appendix B

Description of Data Provided on Disk

All input data required to run the experiments described in this report are contained on either the six companion disks provided with the first phase of this study, or the two disks provided with the second phase. These disks also contain copies of the output reports generated for each of the experiments.

For more efficient operation of The Airport Machine, it is recommended that the data supplied on each floppy disk be transferred to a hard disk drive before attempting to run the simulations. This can be accomplished by using the DOS XCOPY command. For example, to transfer all files from floppy drive B: to hard disk drive C: type:

    XCOPY B:*.* C:\ /S

The files used by each of the 29 experiments of Phase 1 are summarized in table B-1. The files used by the remaining 19 Phase 2 experiments are summarized in table B-2. The data format of these files, meaning of the output report data, and instructions for running the model are described in The Airport Machine User's Manual.

The experiment name in tables B-1 and B-2 is the same as the batch file name used to invoke the proper set of files. With the executable file AMNN.EXE included in the PATH environment, it is necessary only to enter this file name to run an experiment. The prefix of the output report and echo file generated are also the same as the experiment name followed by a .RPT and .ECH suffix, respectively.

In order to ensure simulation results identical to those reported in this study, it is recommended that the same version of The Airport Machine supplied for each phase be used to run simulations included in that same phase.

Airport	Experiment	no.	File			
			RUN	RWC	GEO and RTS	SCRIPT
DFW	BASELINE	1	METESTS	BASELINE	A5WS1	NUL
	MULTEXIT	2	METESTS	MULTEXIT	A5WSMT	NUL
	WOMETHRU	3	THRUPUT	WOMETHRU	A5WS1	SCRIPT
	WMETHRU	4	THRUPUT	WMETHRU	A5WSMT	SCRIPT
	WOMQ	5	WOMQ	INTRAILS	A5WS1	NUL
	MULTQUES	6	MULTQUES	INTRAILS	A5WS1	NUL
DIA	BASELINE	7	DVXZIVSE	DVXZI_SE	DIAZIVSE	NUL
	MULTEXIT	8	DVXZIVSE	DVXMT_SE	DIAMTVSE	NUL
	WOMETHRU	9	DVXZIVSE	WOMETHRU	DIAZIVSE	SCRIPT
	WMETHRU	10	DVXZIVSE	WMETHRU	DIAMTVSE	SCRIPT
IAD	BASELINE	11	IAD00S	IAD00___	IAD0MS	NUL
	MULTEXIT	12	IAD00S	IADME___	IADMMS	NUL
	WOMETHRU	13	THRUPUT	WOMETHRU	IAD0MS	SCRIPT
	WMETHRU	14	THRUPUT	WMETHRU	IADMMS	SCRIPT
	WOMQ	15	MQ	MQTEST	1FT0M	NUL
	2FLTCAP	16	MQ	MQTEST	500FT0M	NUL
	4FLTCAP	17	MQ	MQTEST	1000FT0M	NUL
	6FLTCAP	18	MQ	MQTEST	1500FT0M	NUL
JFK	BASELINE	19	KIAPSVSE	KIAPS___	KIAPSVSE	NUL
	MULTEXIT	20	KIAPSVSE	KIAMT___	KIAMTVSE	nul
	WOMETHRU	21	KIAPSVSE	WOMETHRU	KIAPSVSE	SCRIPT
	WMETHRU	22	KIAPSVSE	WMETHRU	KIAMTVSE	SCRIPT
PHL	BASELINE	23	PHL88VWS	PHL88___	PHL88VWS	NUL
	MULTEXIT	24	PHL88VWS	PHLMT___	PHLMEVWS	NUL
	WOMETHRU	25	THRUPUT	WOMETHRU	PHLMCVWS	SCRIPT
	WMETHRU	26	THRUPUT	WMETHRU	PHLMTVWS	SCRIPT
	MULTCROS	27	PHL88VWS	PHL88___	PHLMCVWS	NUL
SEA	BASELINE	28	SEASV88	SEA88	SEA88_S_	NUL
	BOTH	29	SEASV88	SEAMT	SEAMT_S_	NUL

Table B-1   Listing of Experiments and Associated Input Files

AIRPORT	BATCH	EXPERIMENT	RUN	RWC	GTS	SCH	GEO and RTS	SCRIPT
PHL	womethru	30	tp	womethru	phl88	phlmtv	phlmcvws	script
	womefm2	31	tp	womethru	phl88	phlfm2	phlmcvws	script
	womefm3	32	tp	womethru	phl88	phlfm3	phlmcvws	script
	wmethru	33	tp	wmethru	phl88	phlmtv	phlmtvws	script
	wmefm2	34	tp	wmethru	phl88	phlfm2	phlmtvws	script
	wmefm3	35	tp	wmethru	phl88	phlfm3	phlmtvws	script
	multexit	36	phl88vws	phlmt	phl91	large	phlmevws	nul
	multtaxi	37	phl88vws	phlmt	phl91	large	phlmgvws	nul
	medual	38	phl88vws	phlmt	phl91	large	phldeyws	nul
	woexthru	39	tp	woex	phl88	phlmtv	phlmtvws	script
	wexthru	40	tp	ex	phl88	phlmtv	phlmtvws	script
IAD	womethru	41	thruput	womethru	iad00	iadmt	iad0ms	script
	womefm2	42	thruput	womethru	iad00	iadfm2	iad0ms	script
	womefm3	43	thruput	womethru	iad00	iadfm3	iad0ms	script
	wmethru	44	thruput	wmethru	iad00	iadmt	iadmms	script
	wmefm2	45	thruput	wmethru	iad00	iadfm2	iadmms	script
	wmefm3	46	thruput	wmethru	iad00	iadfm3	iadmms	script
	multexit	47	iad00s	iadme	iad00	new	iadgms	nul
	multtaxi	48	iad00s	iadme	iad00	new	iadgms	nul

Table B-2   Listing of Phase 2 Experiments and Associated Input Files

Appendix C

Airport Configurations Simulated
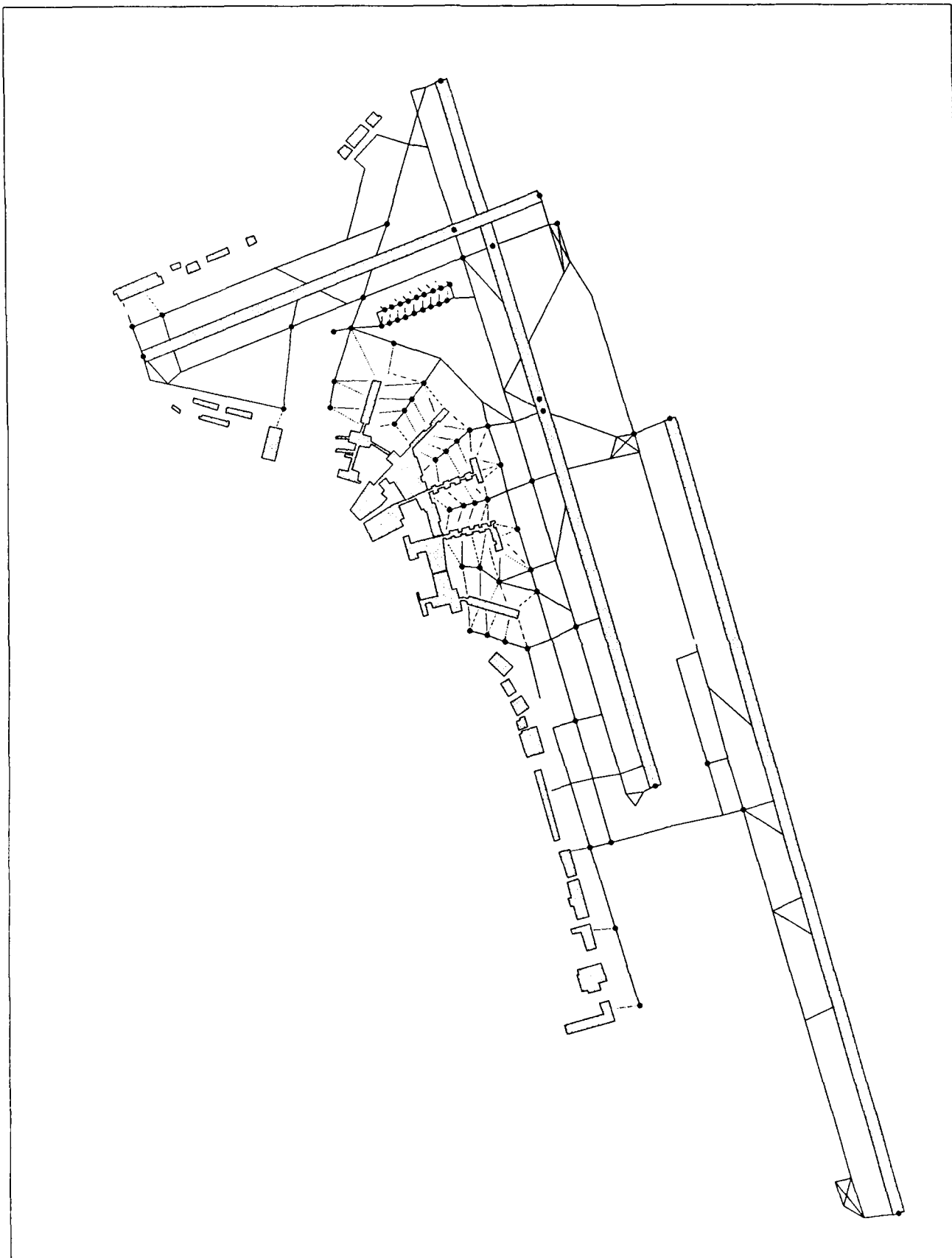
Fig. C-1　PHL Full View
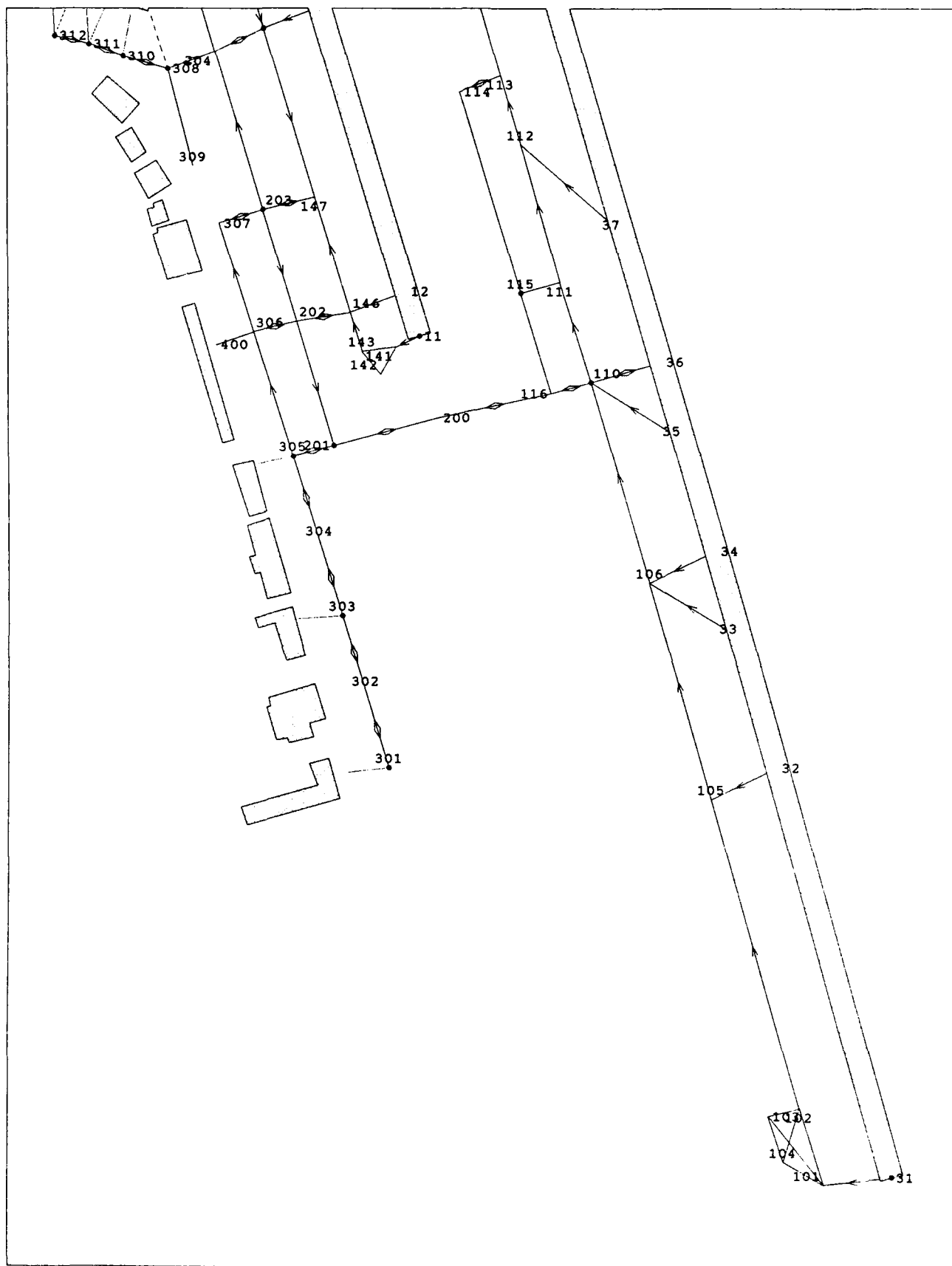
Fig. C-2 PHL Left Side
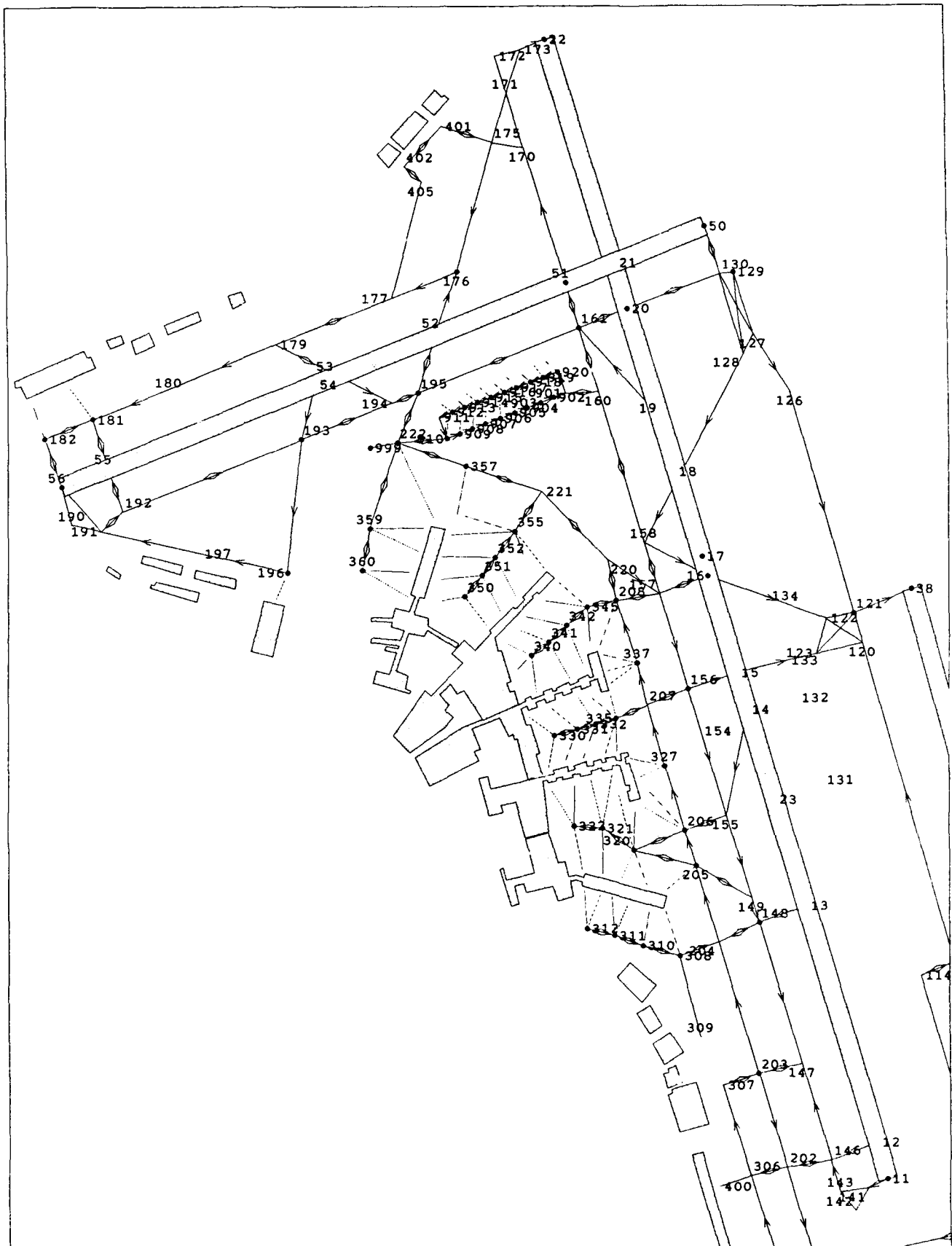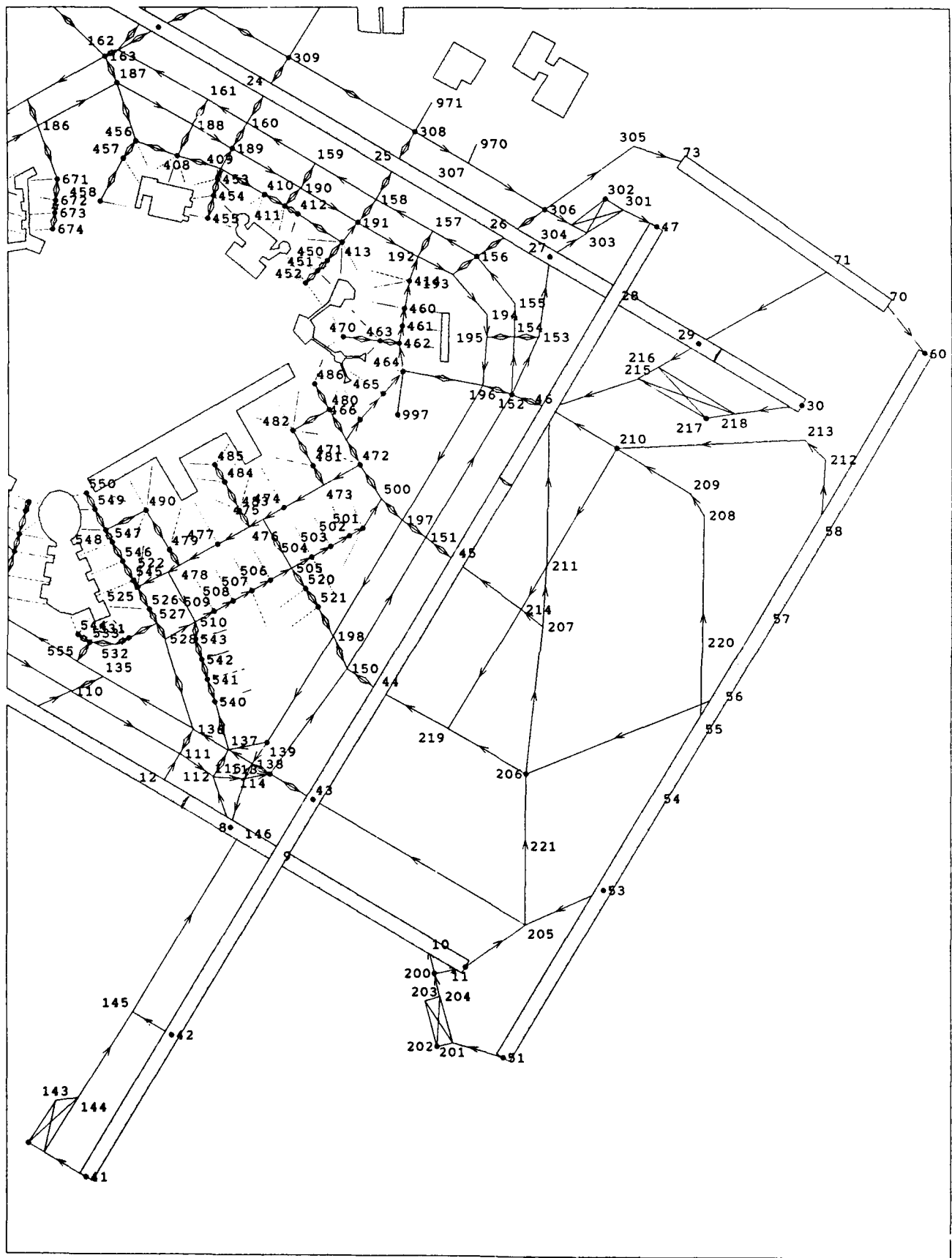
Fig. C-3   PHL Right Side Without Multipath Exits
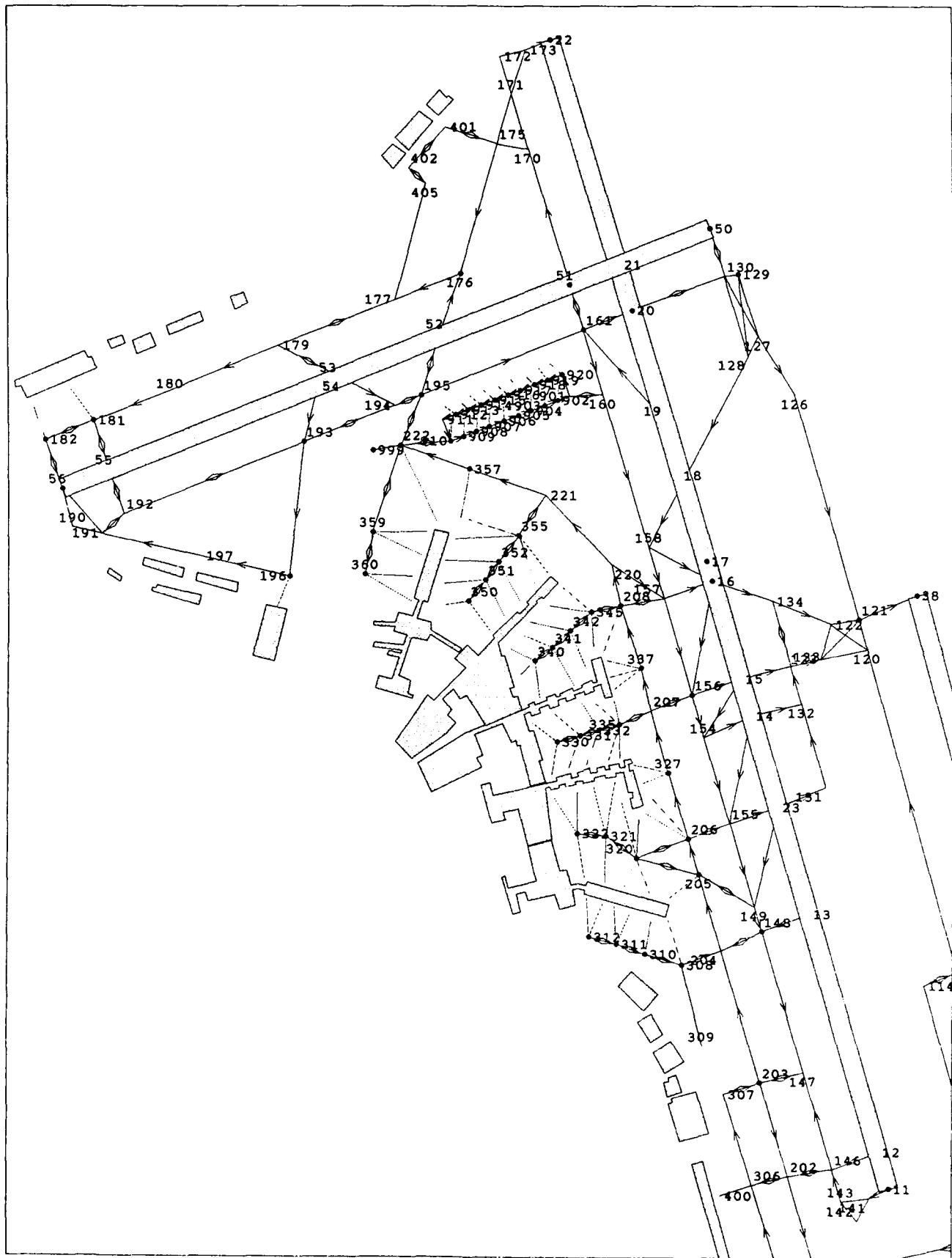
Fig. C-4   PHL Right Side With Multipath Exits

Fig. C-5   PHL Terminal Area
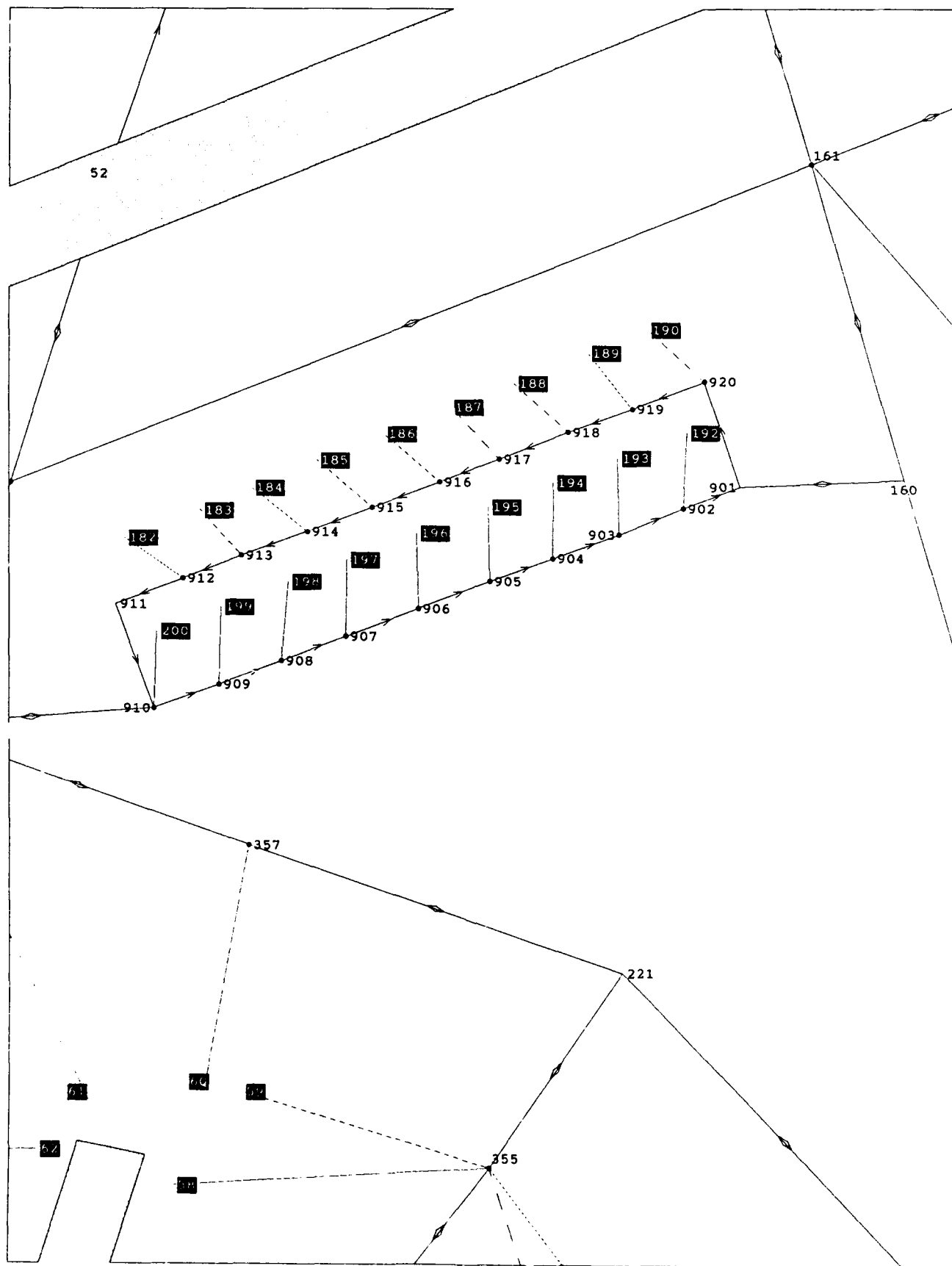
Fig. C-6   PHL Commuter Gate Area
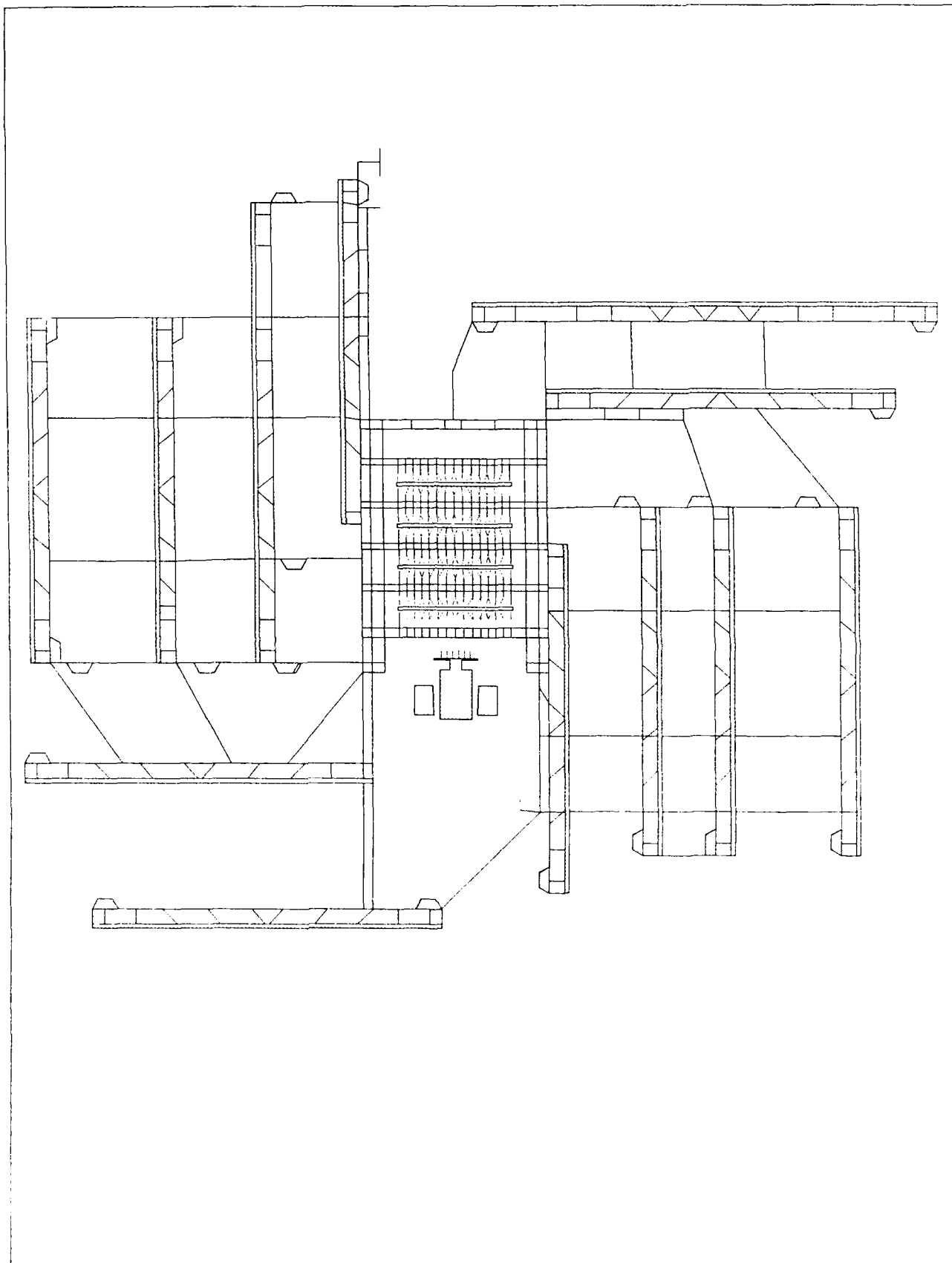
Fig. C-7   DIA Full View
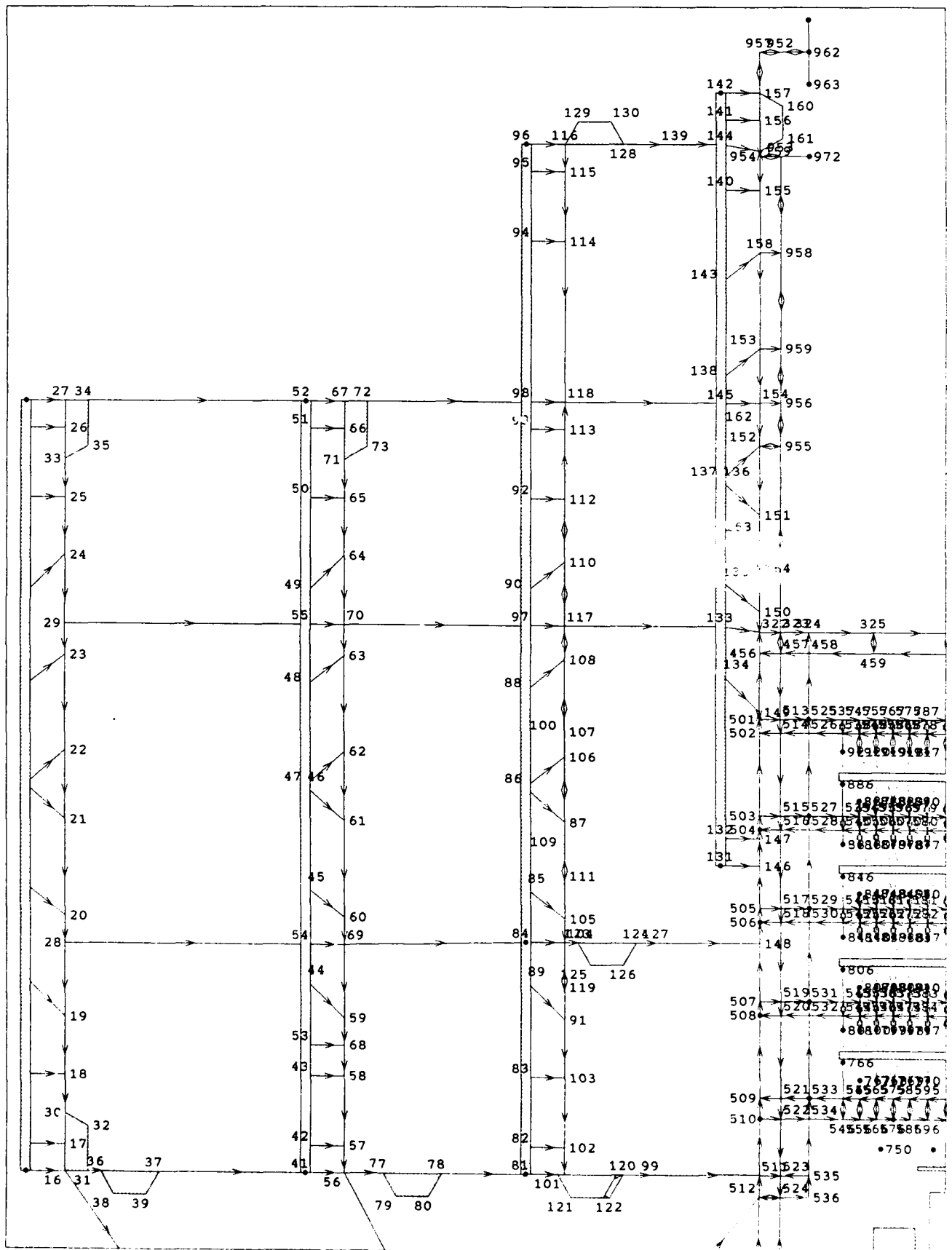
Fig. C-8   DIA Without Multipath Exits - Upper Left
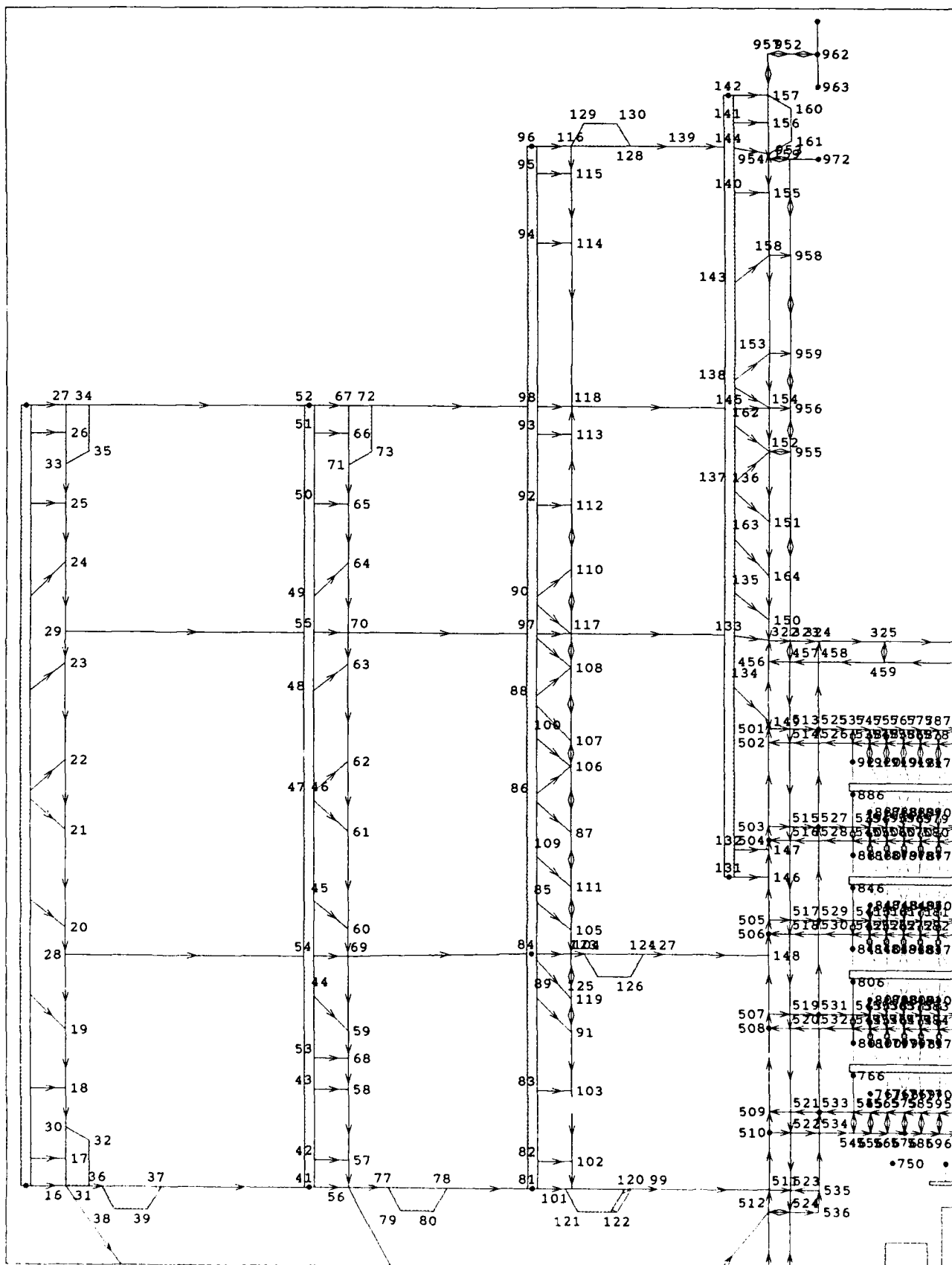
Fig. C-9   DIA With Multipath Exits - Upper Left

Fig. C-10   DIA Bottom Left
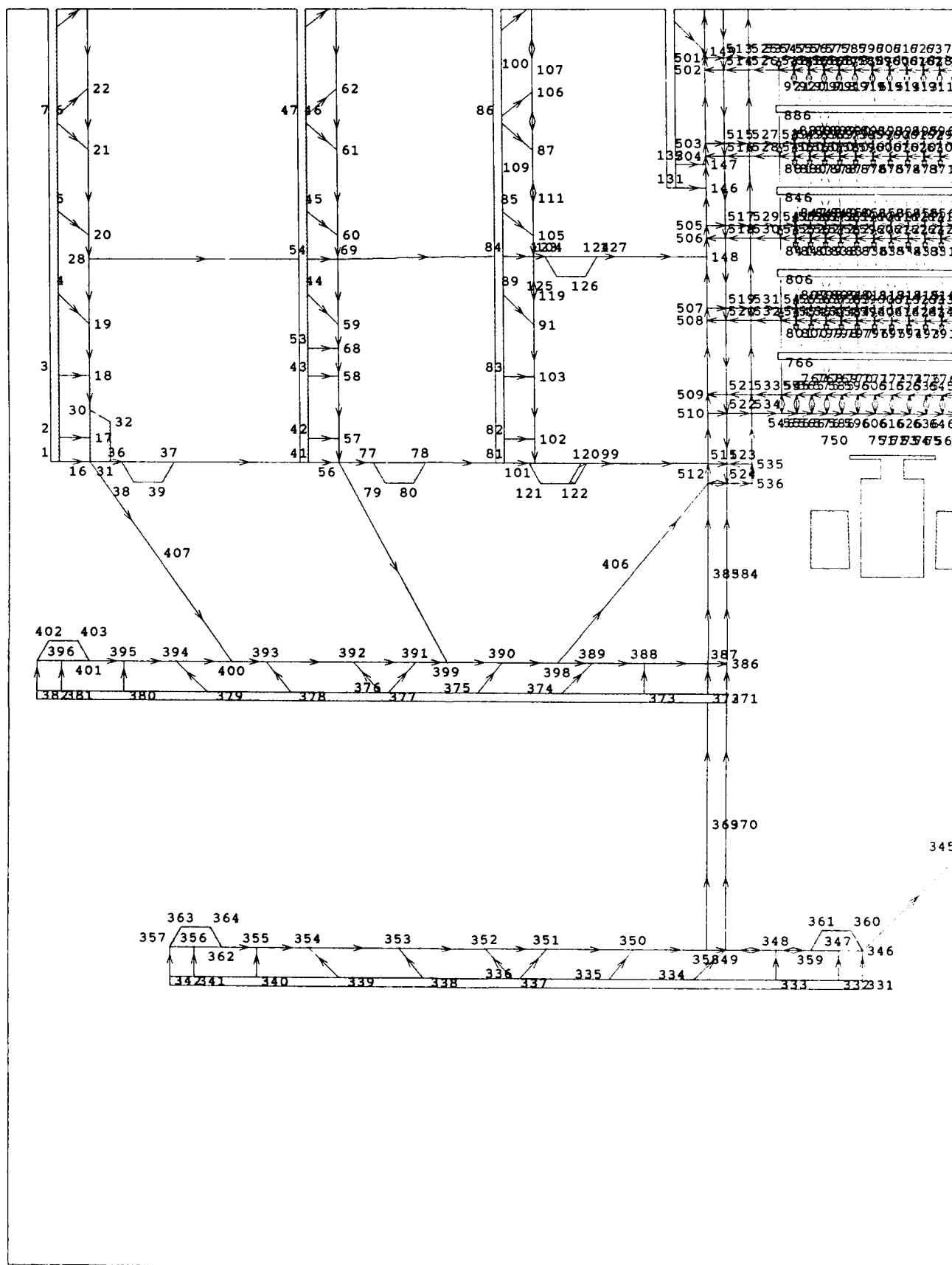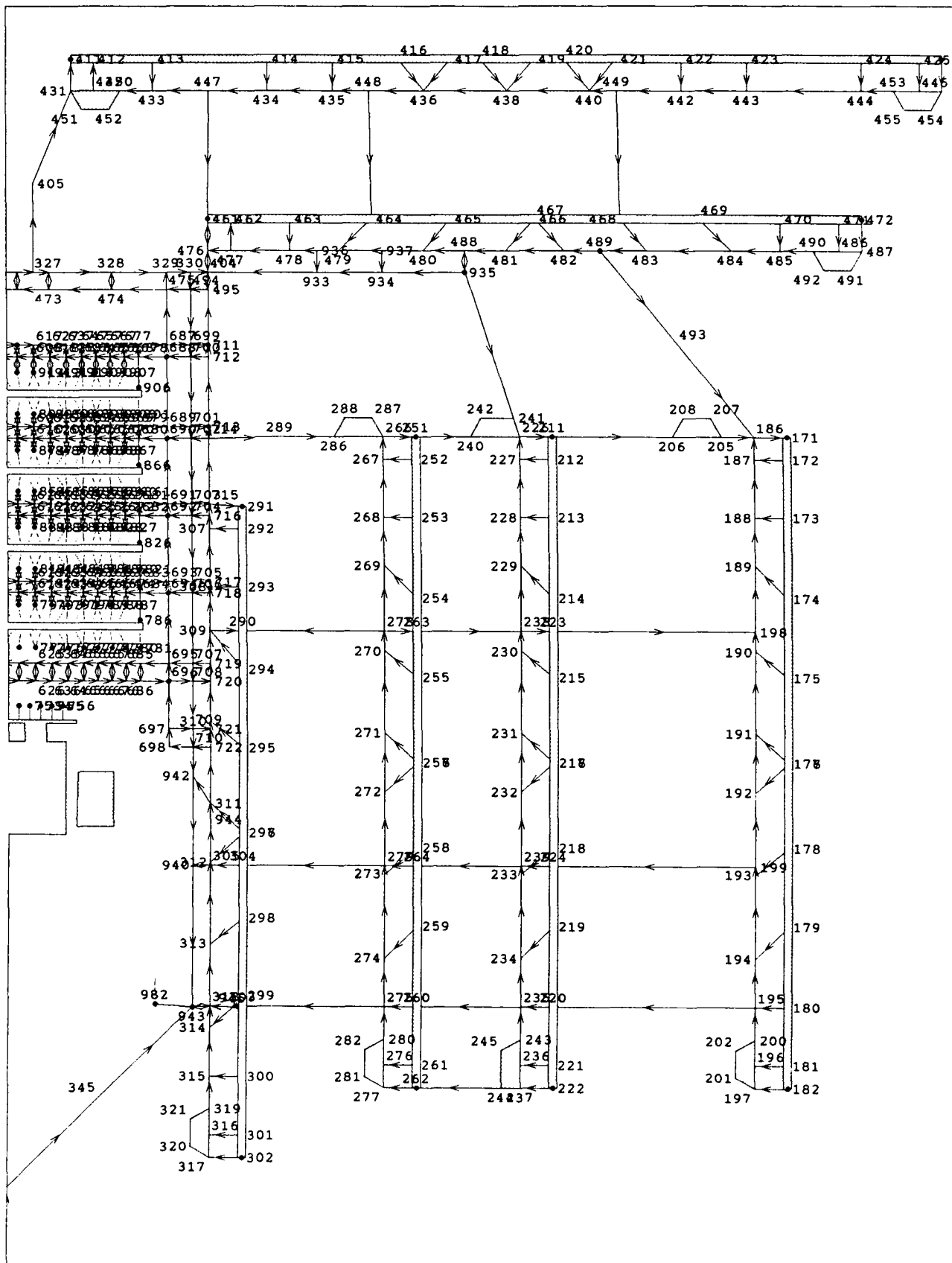
Fig. C-11   DIA Right Side
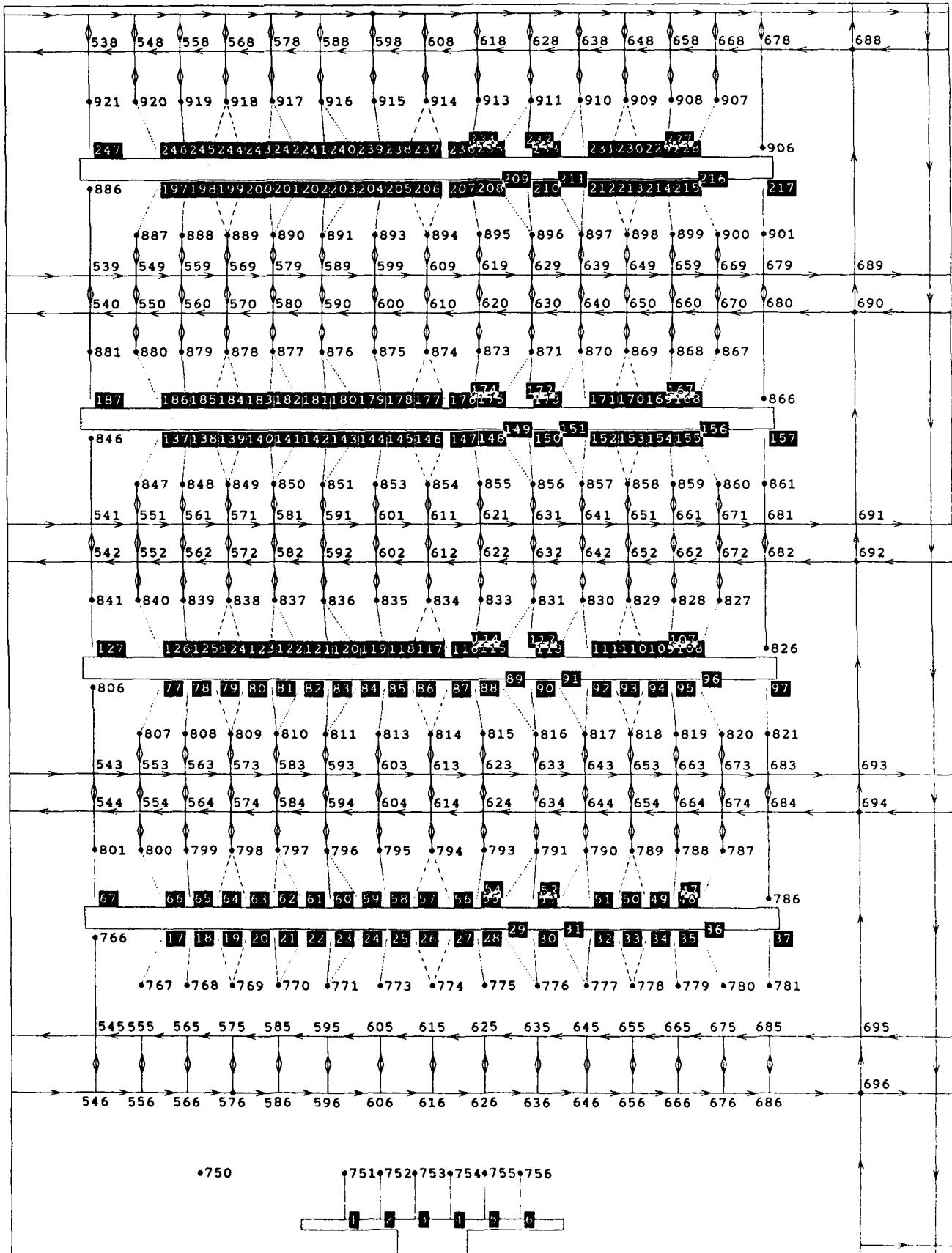
Fig. C-12   DIA Gate Area
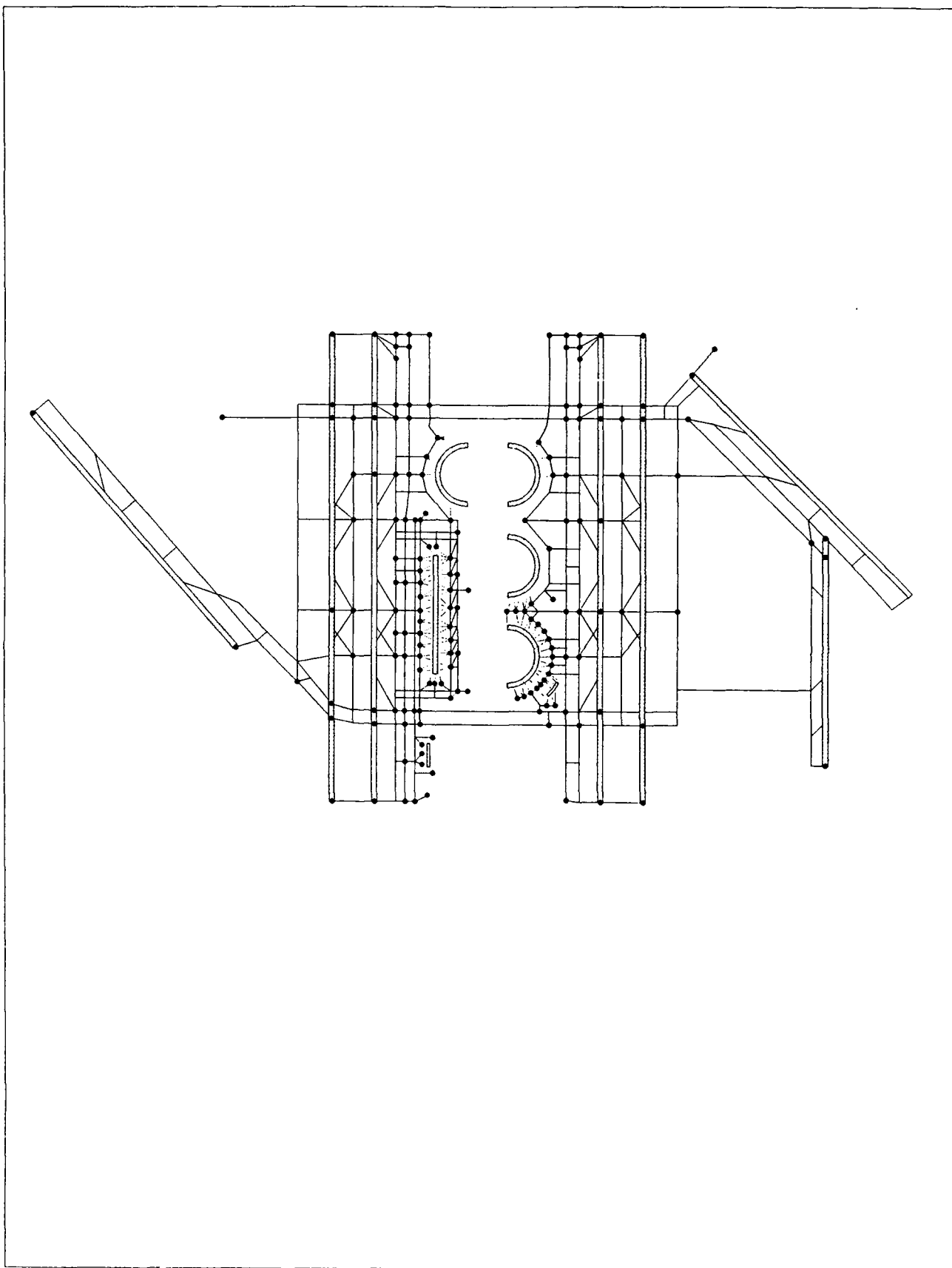
Fig. C-13   DFW Full View
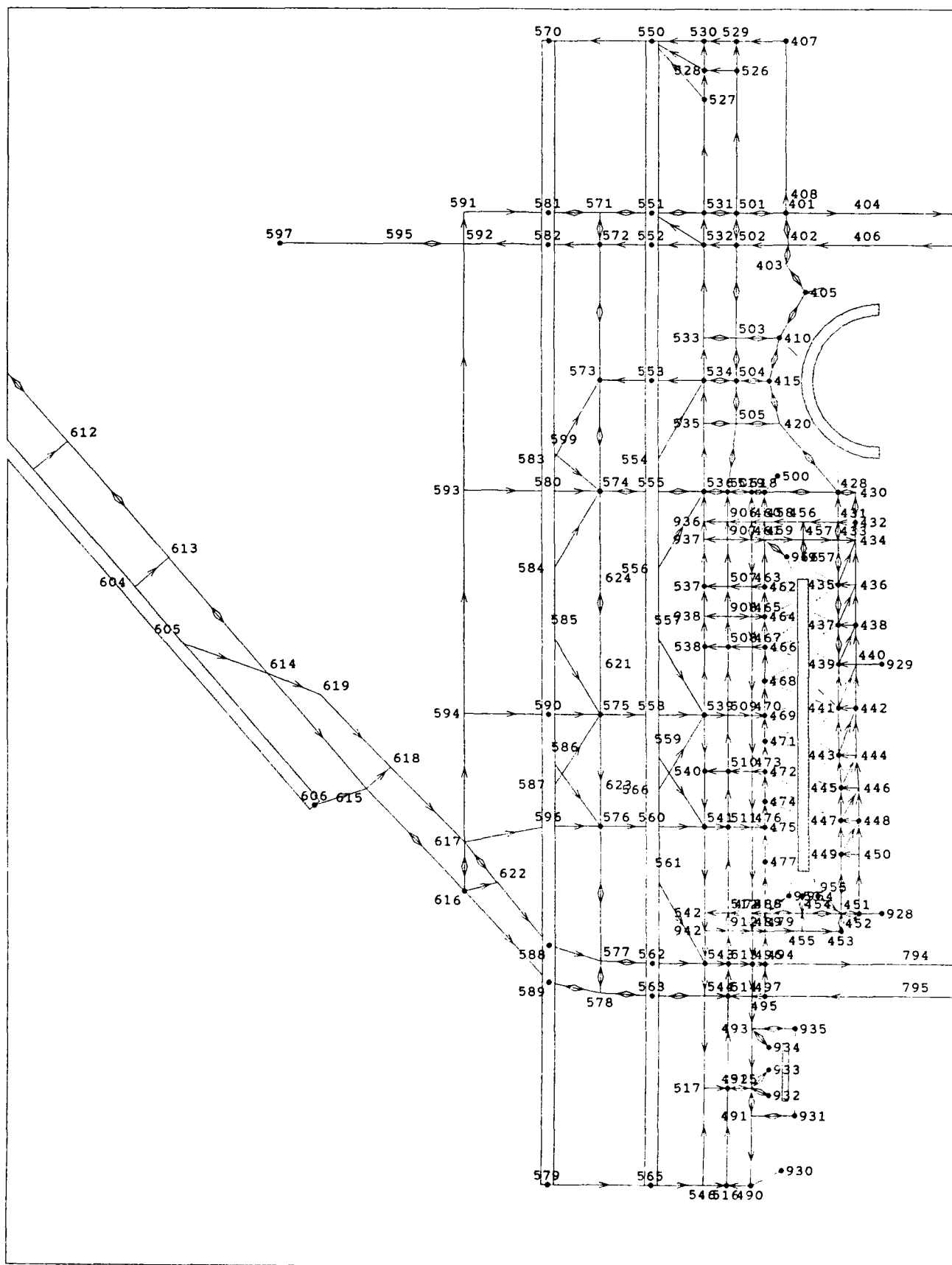
Fig. C-14   DFW Left Side Without Multipath Exits
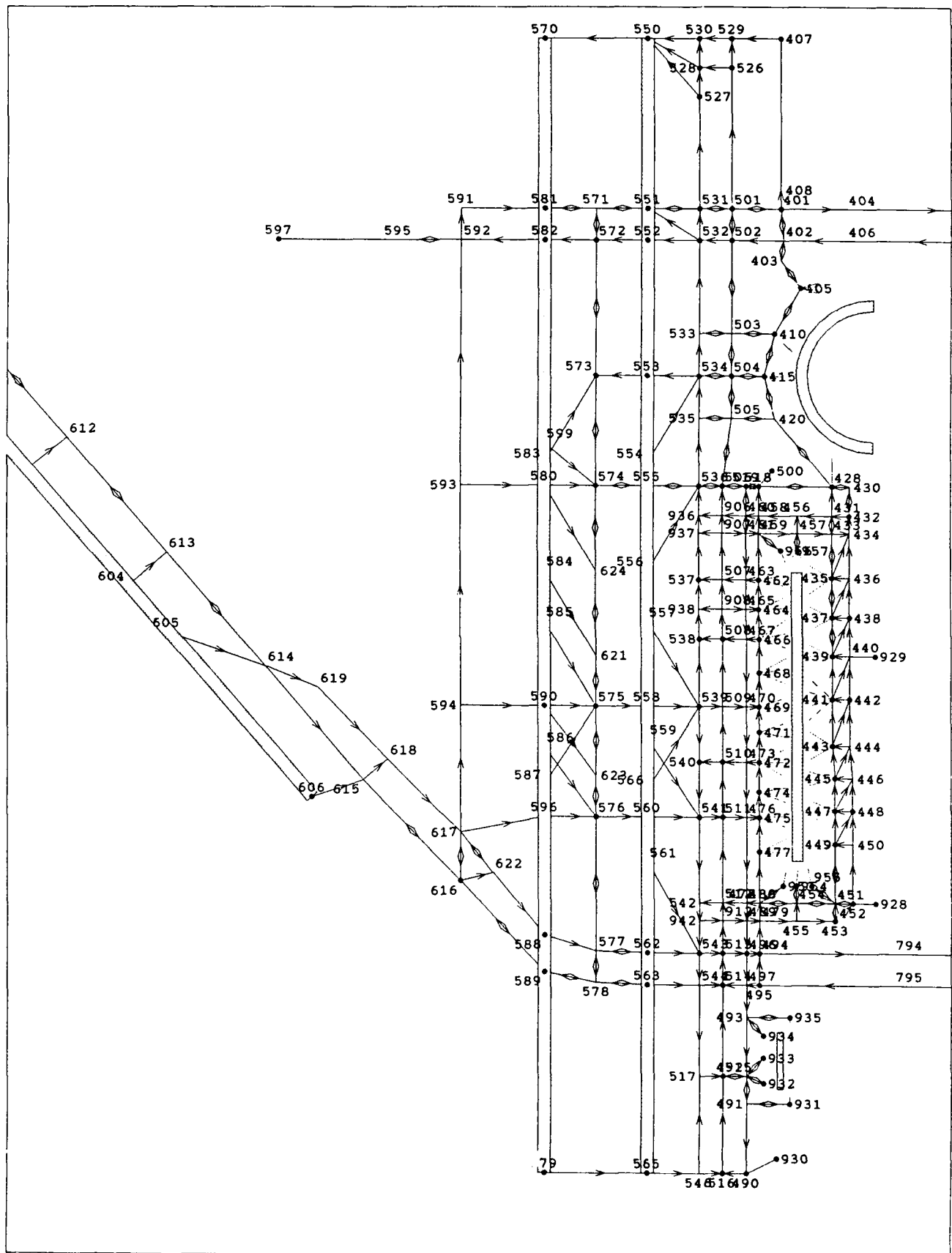
Fig. C-15   DFW Left Side With Multipath Exits
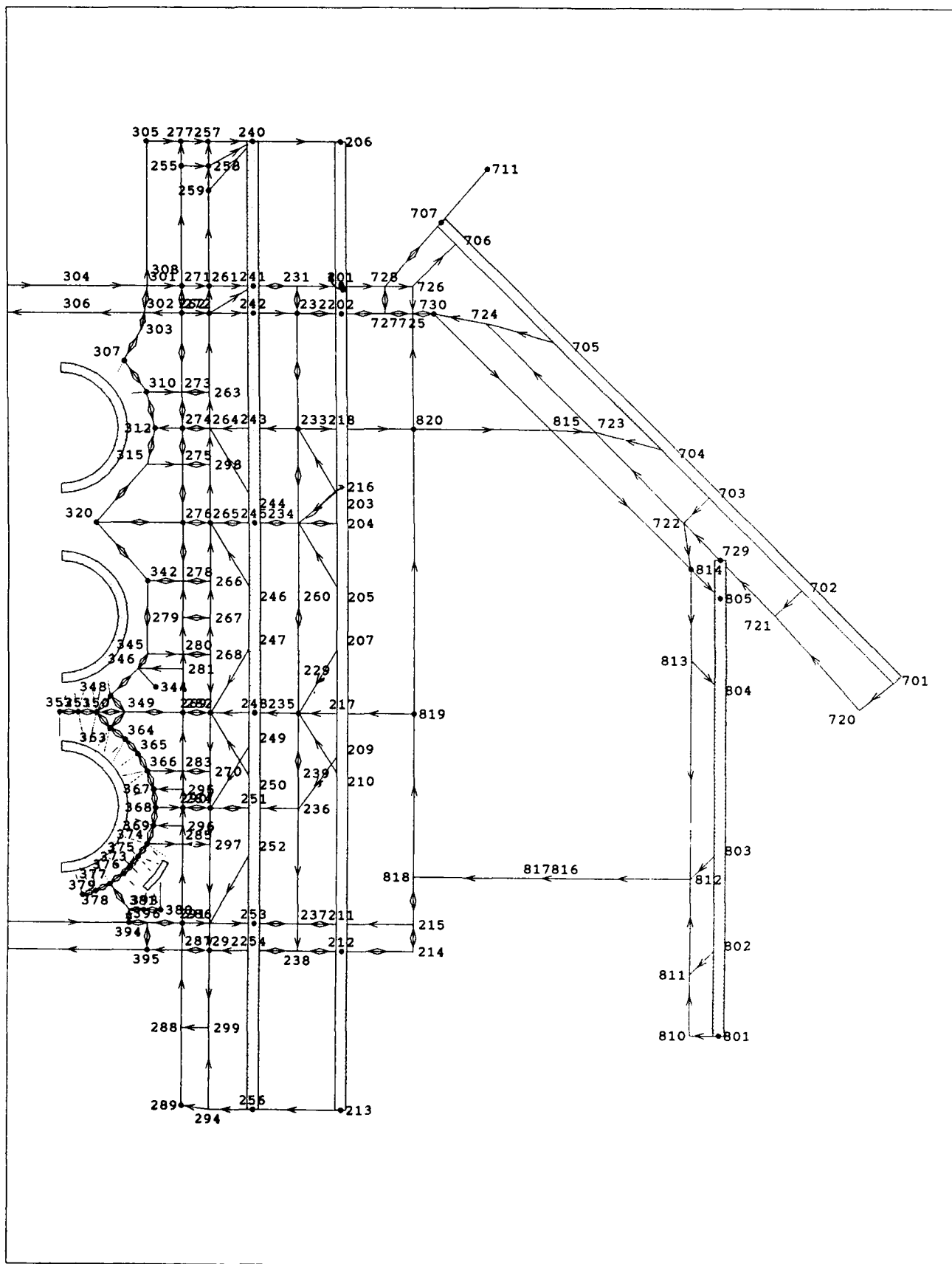
Fig. C-16   DFW Right Side Without Multipath Exits
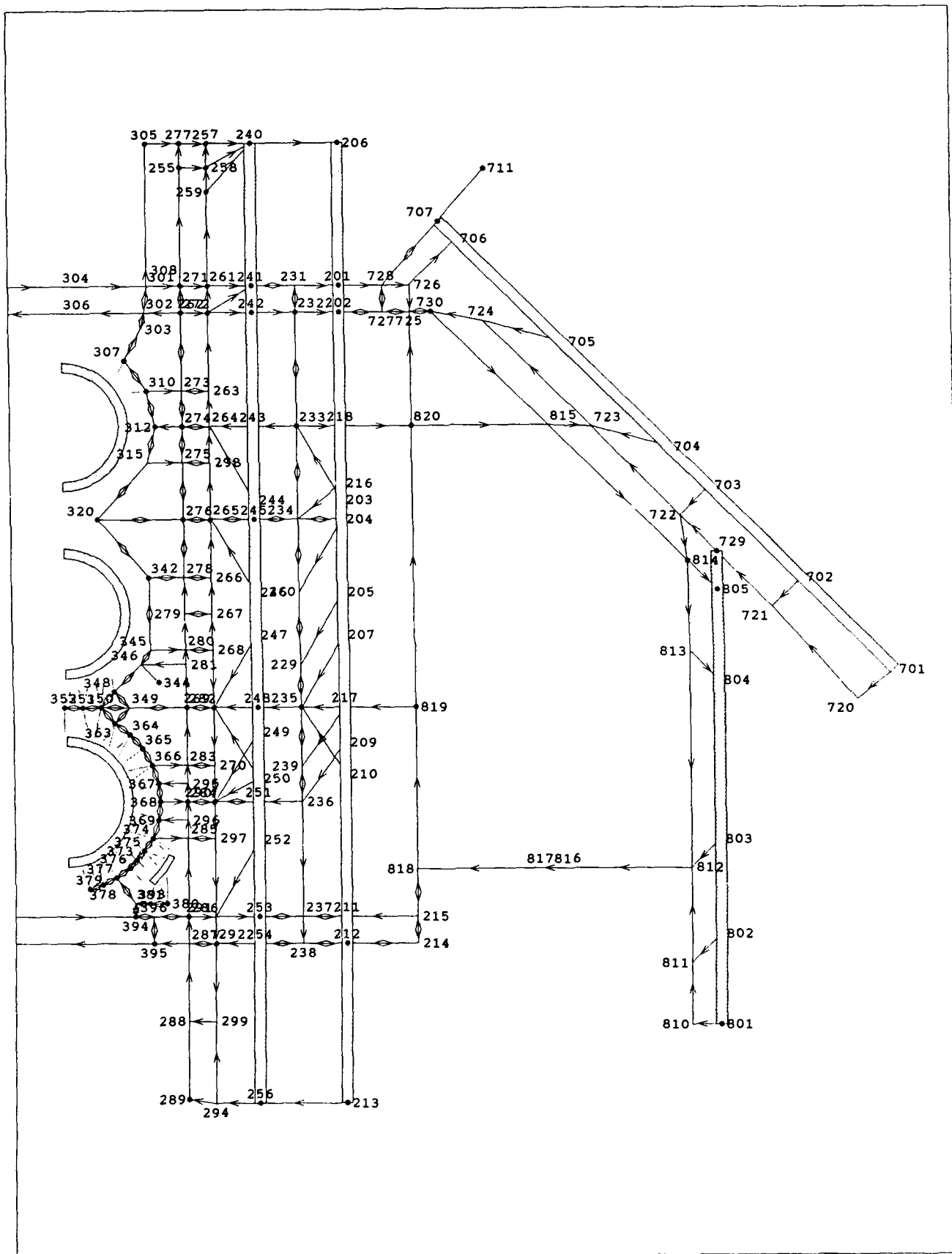
Fig. C-17   DFW Right Side With Multipath Exits

Fig. C-18   DFW Gate Area
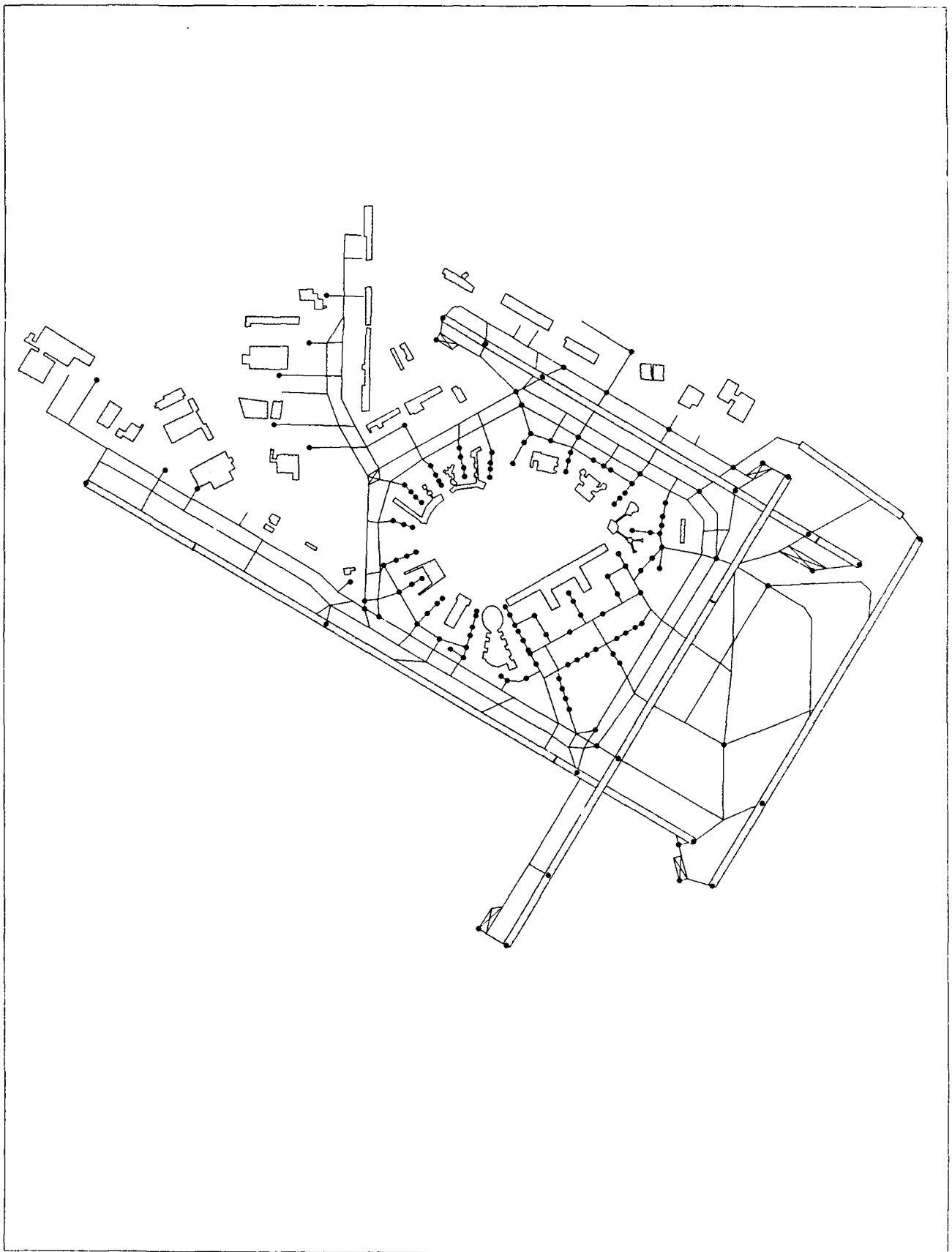
Fig. C-19   JFK Full View
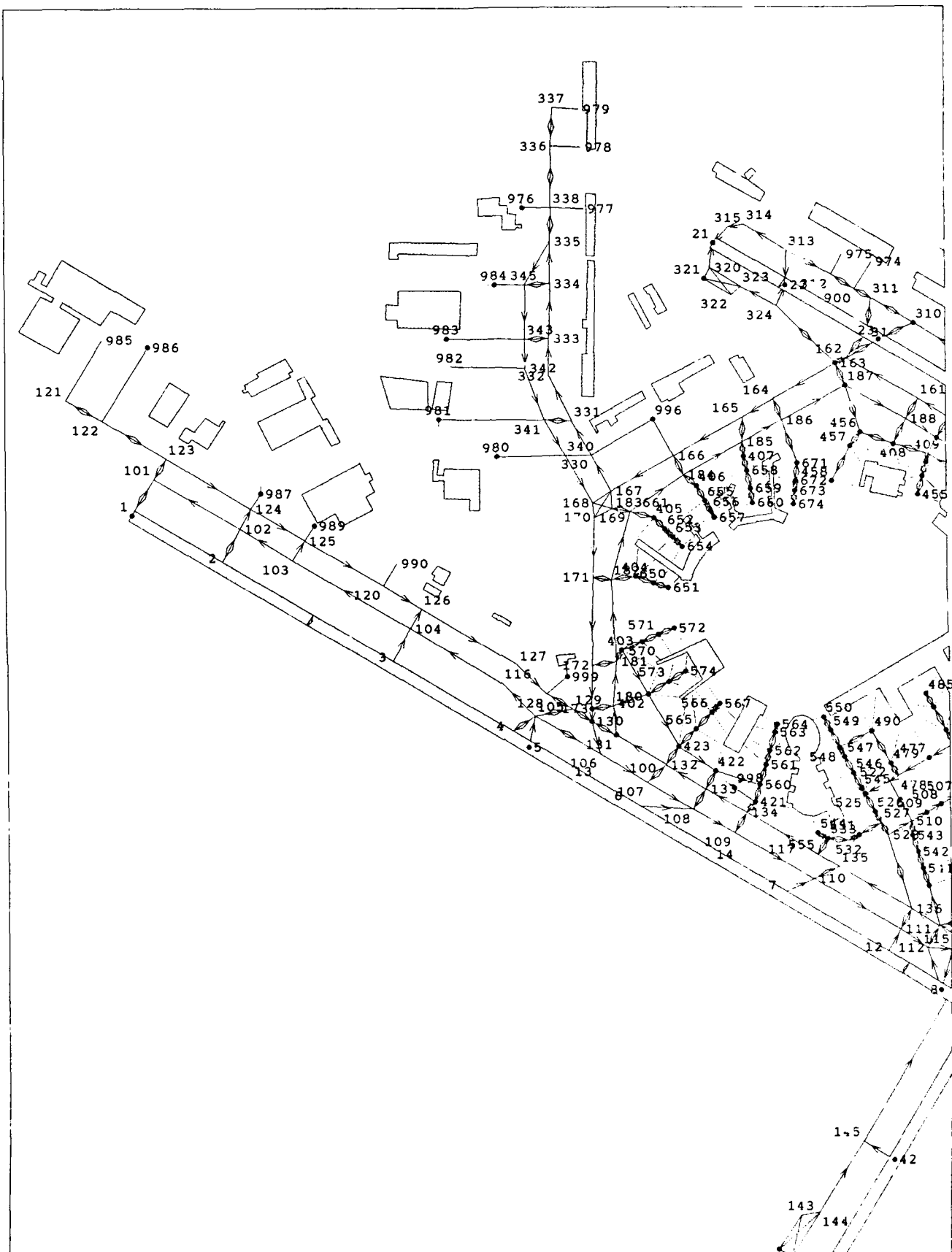
Fig. C-20   JFK Left Side Without Multipath Exits
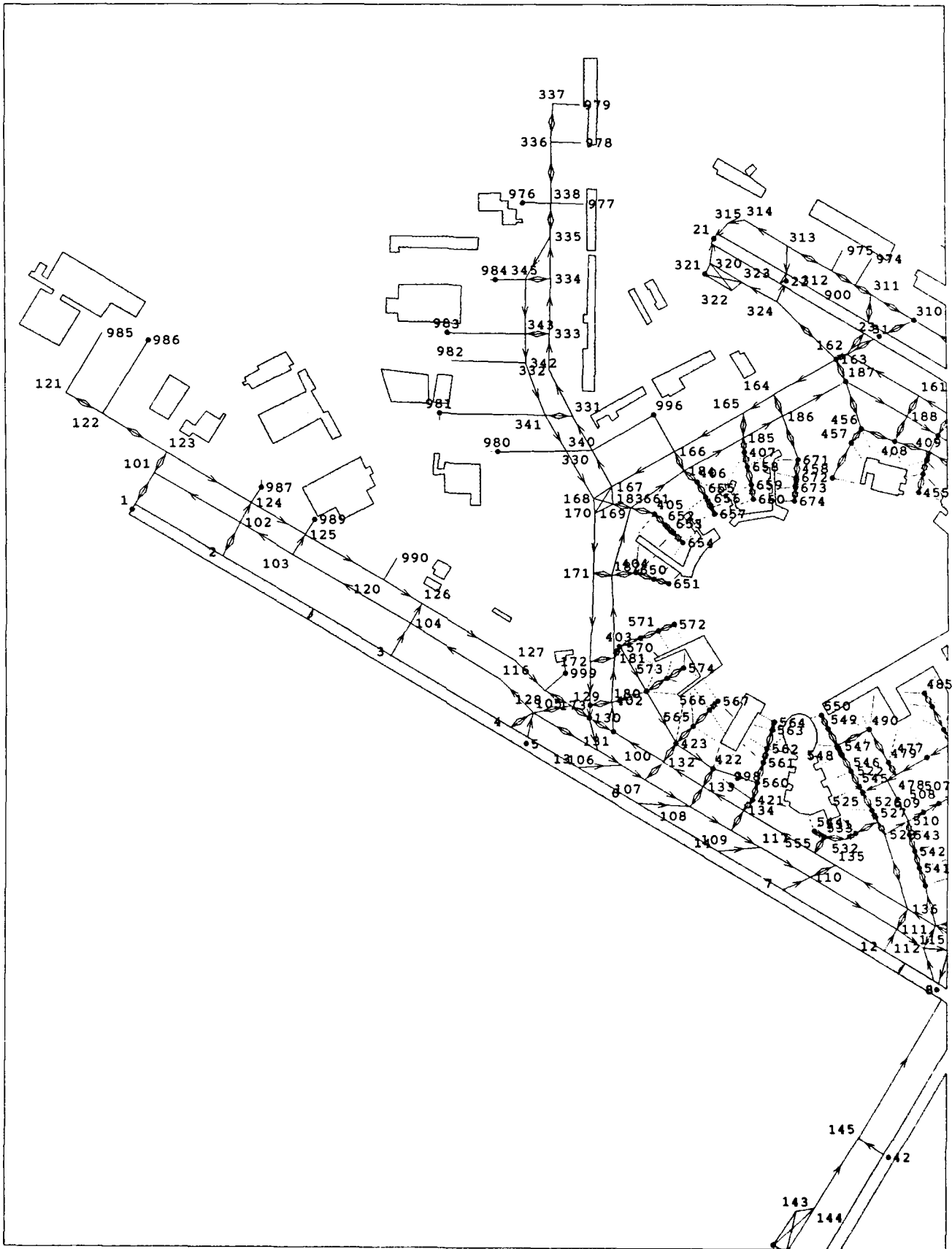
Fig. C-21   JFK Left Side With Multipath Exits

Fig. C-22   JFK Right Side Without Multipath Exits
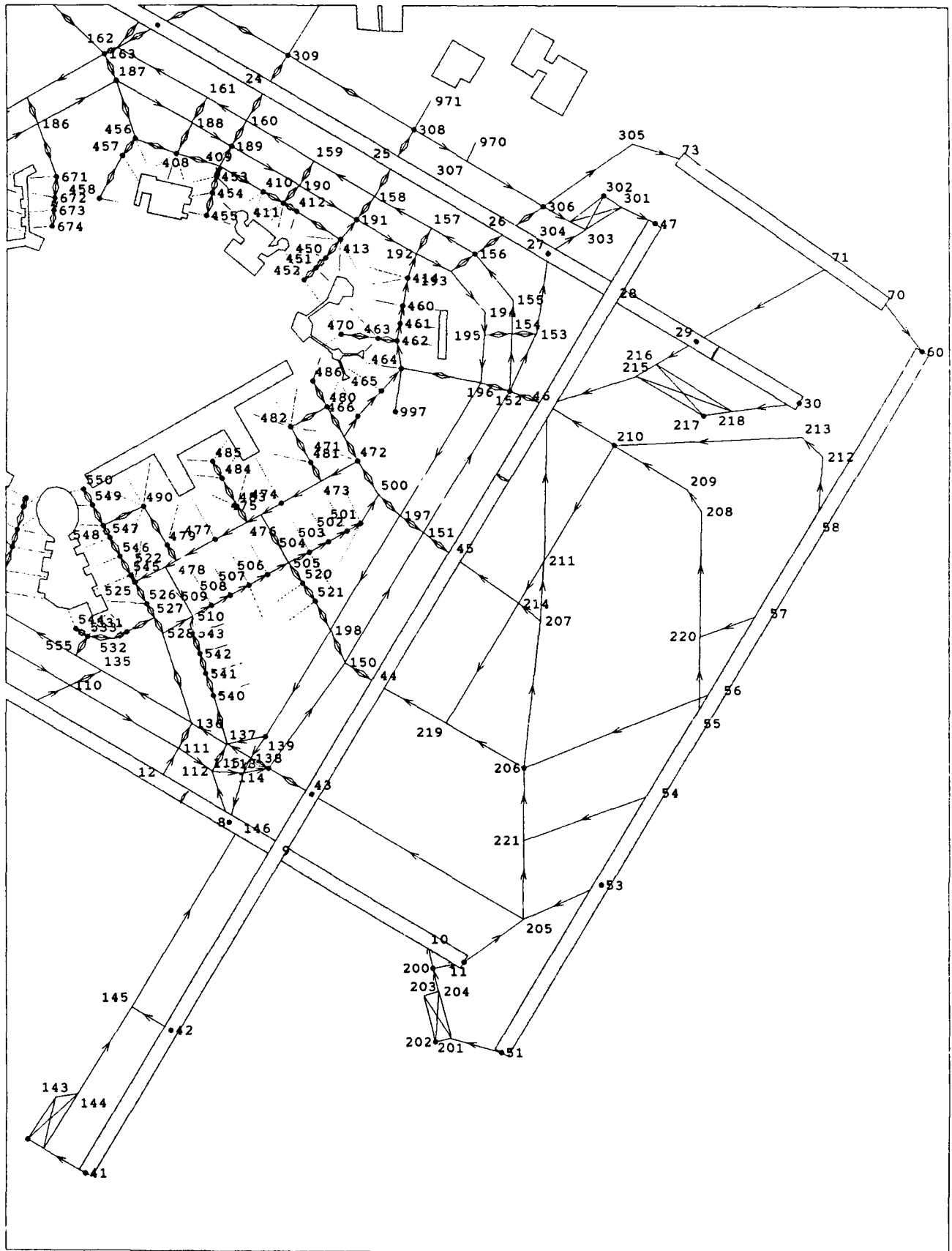
Fig. C-23 JFK Right Side With Multipath Exits
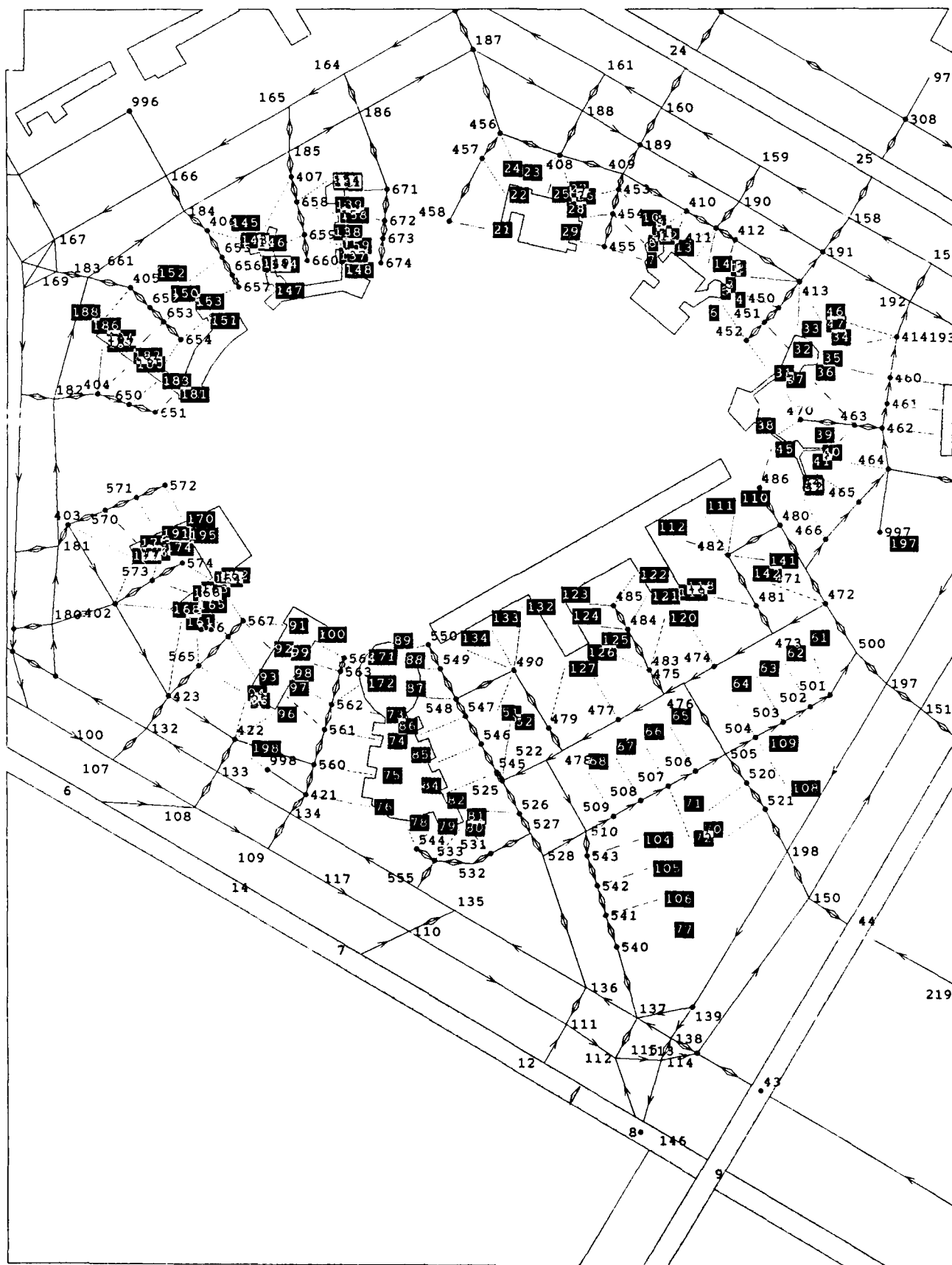
Fig. C-24   JFK Gate Area
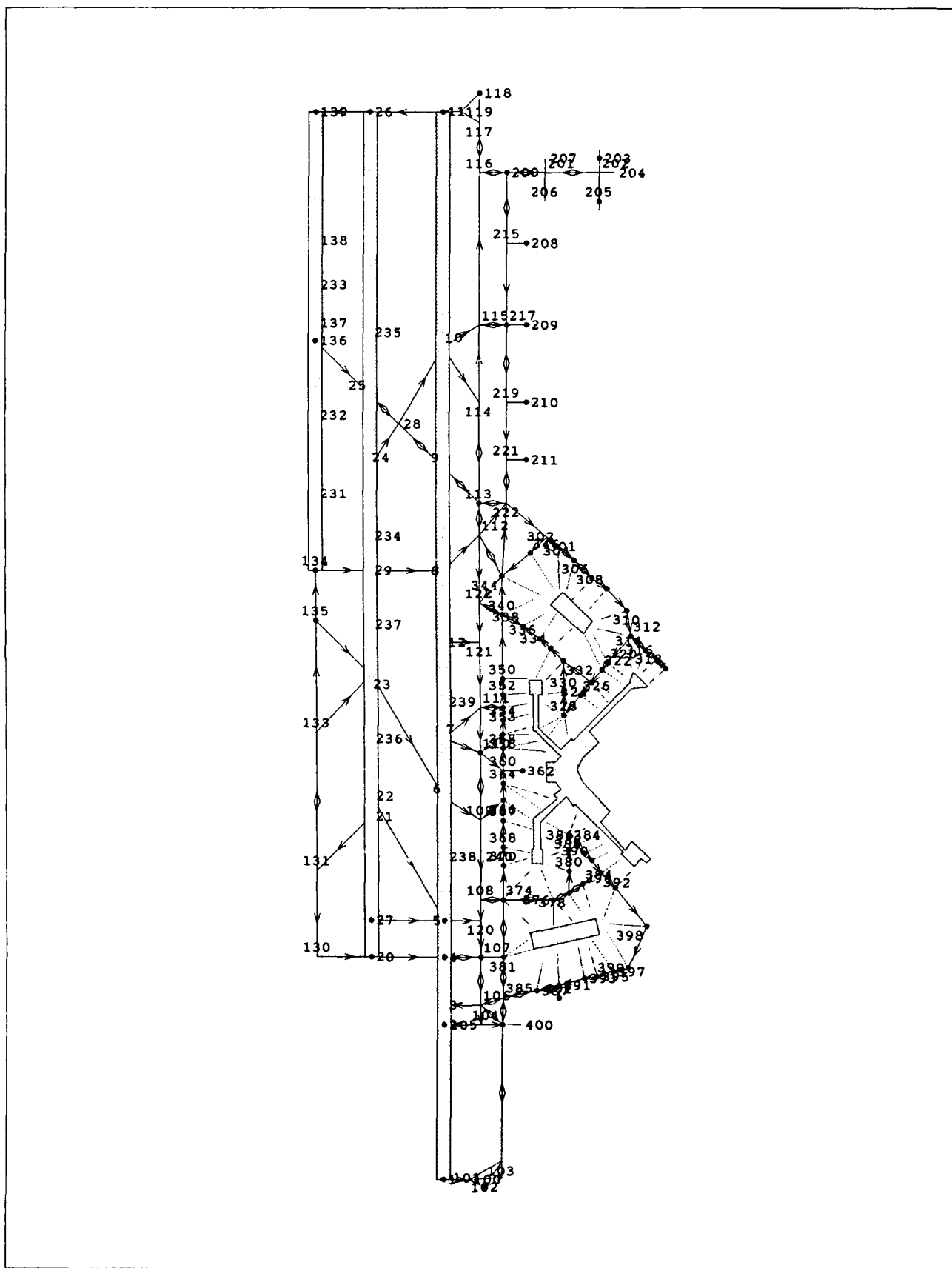
Fig. C-25   SEA Full View Without Multipath Exits and Multiple Crossings
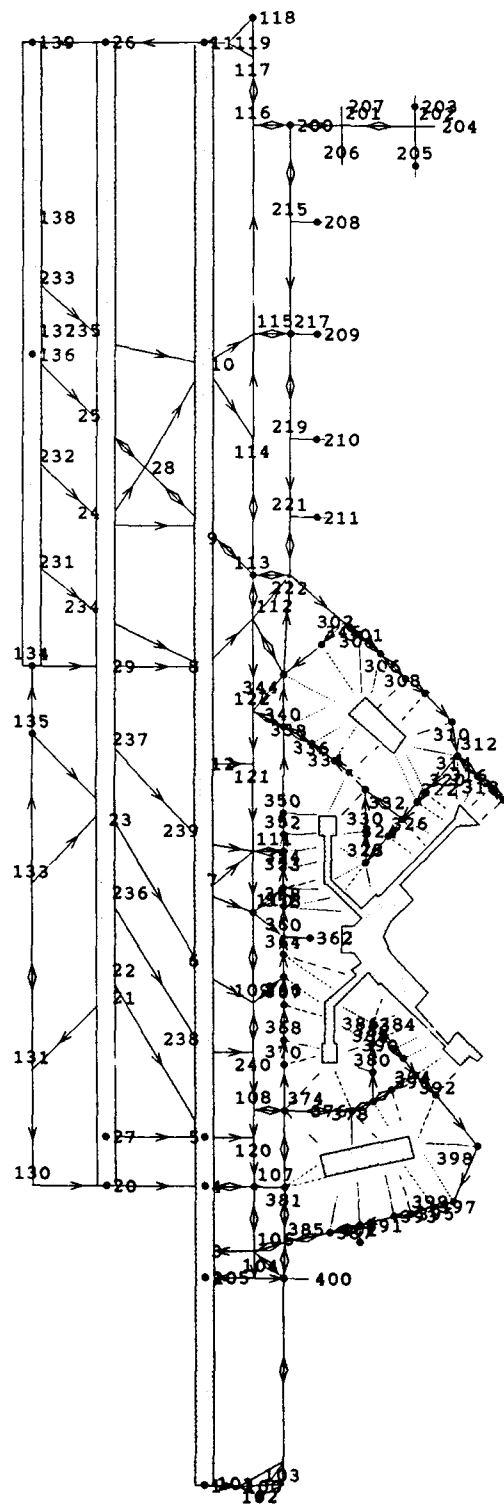
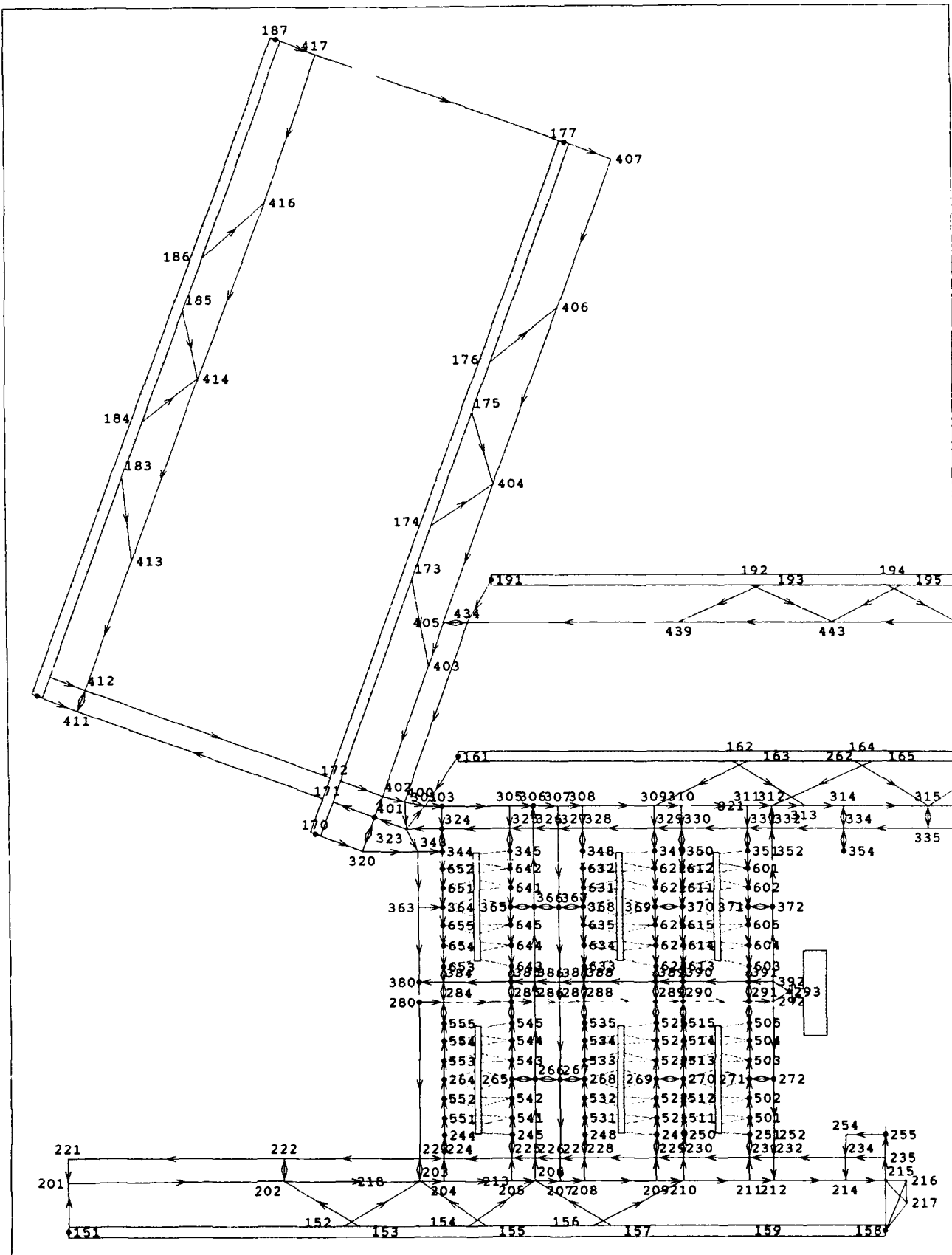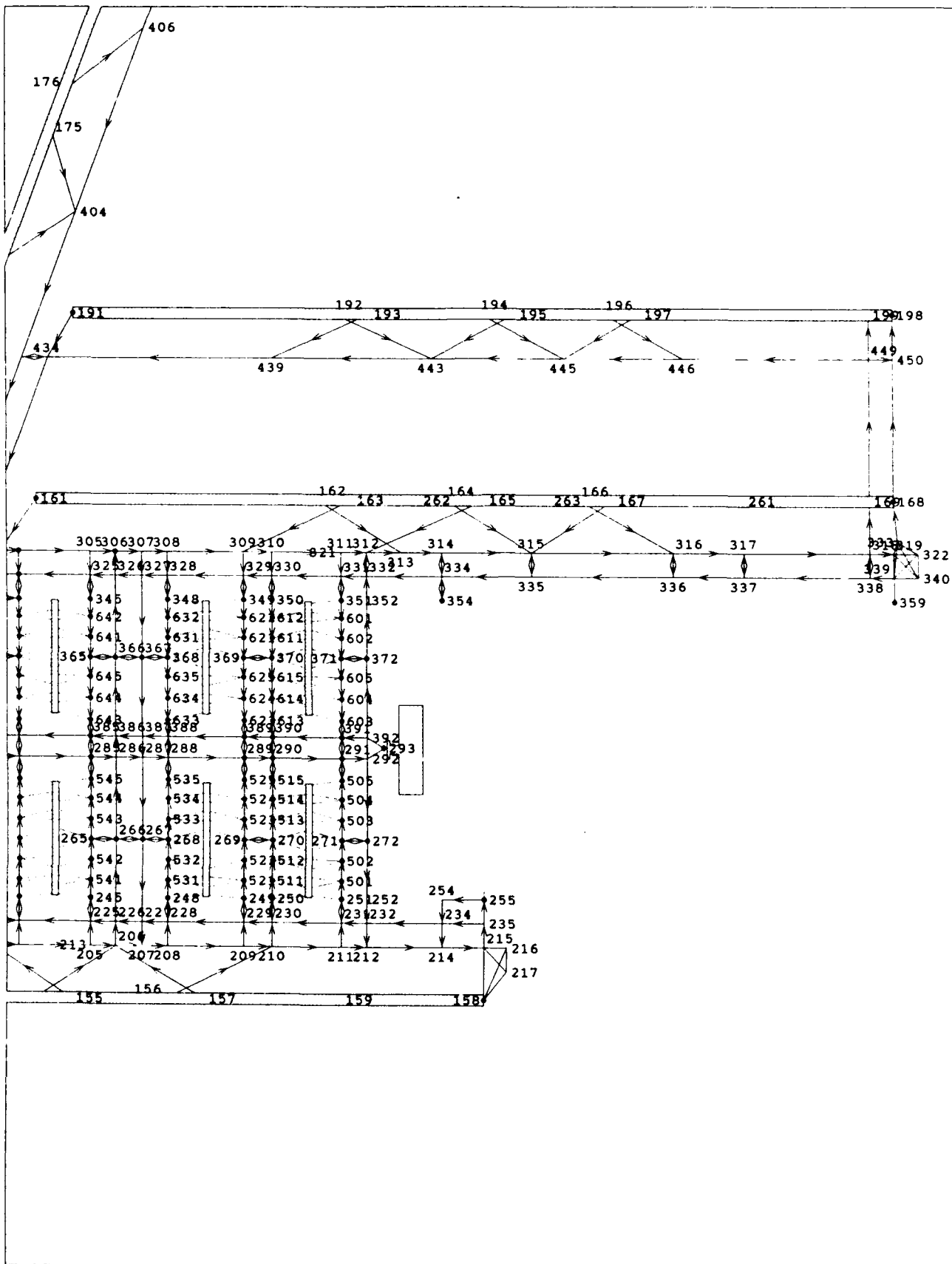Fig. C-26   SEA Full View With Multipath Exits and Multiple Crossings

Fig. C-27   SEA Gate Area
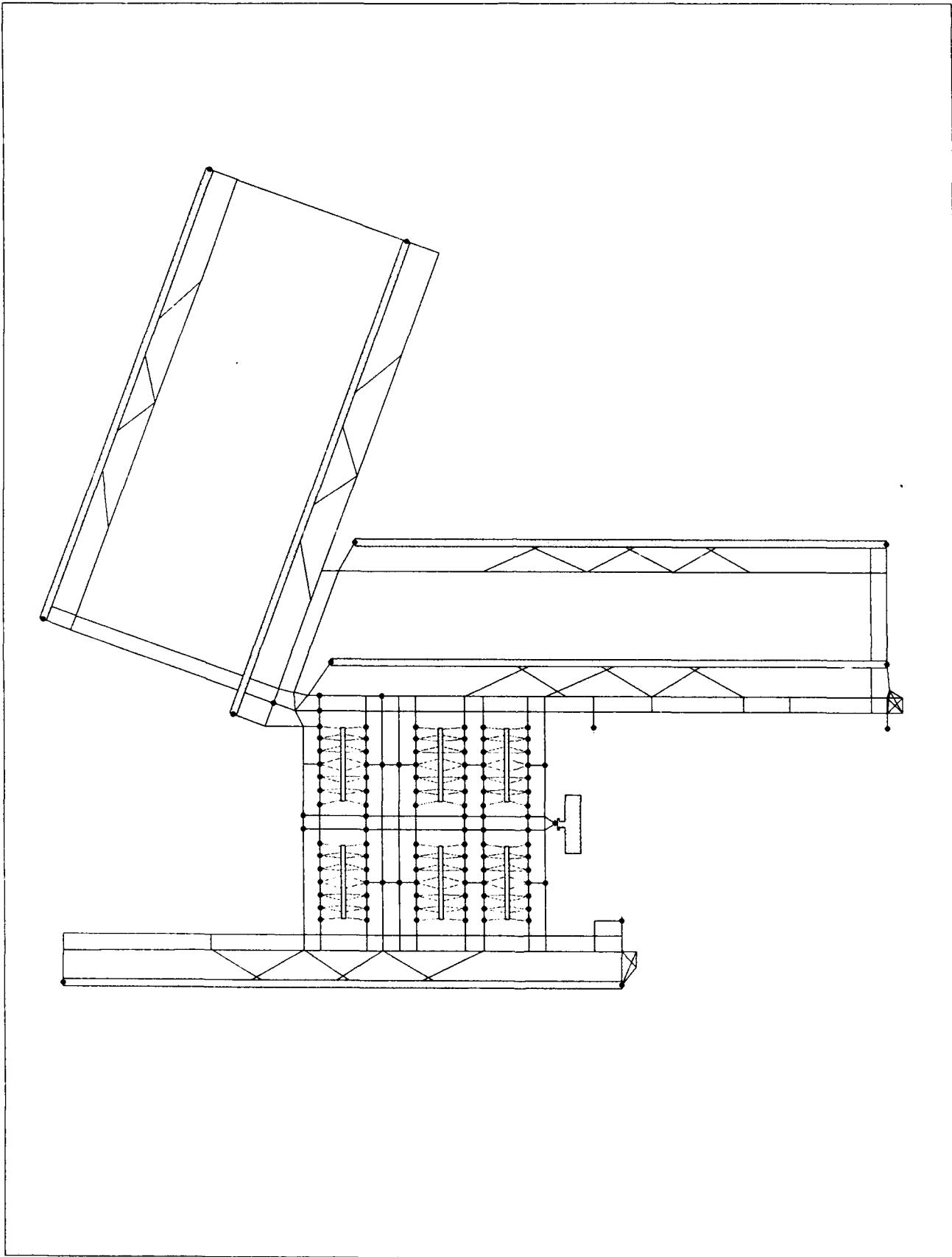
Fig.C-28   IAD Full View

Fig.C-29   IAD Left Side

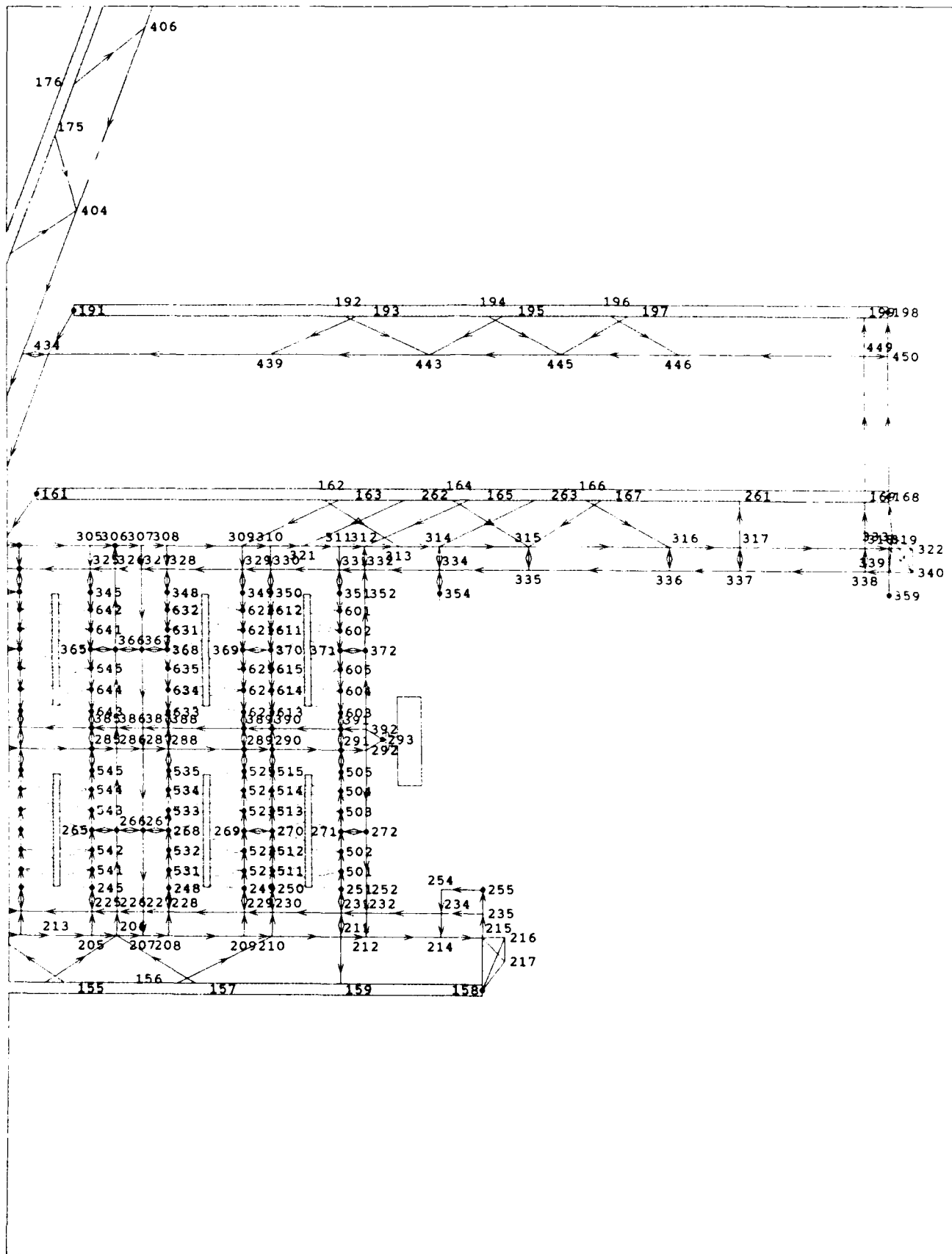Fig.C-30   IAD Right Side Without Multipath Exits

Fig. C-31   IAD Right Side With Multipath Exits

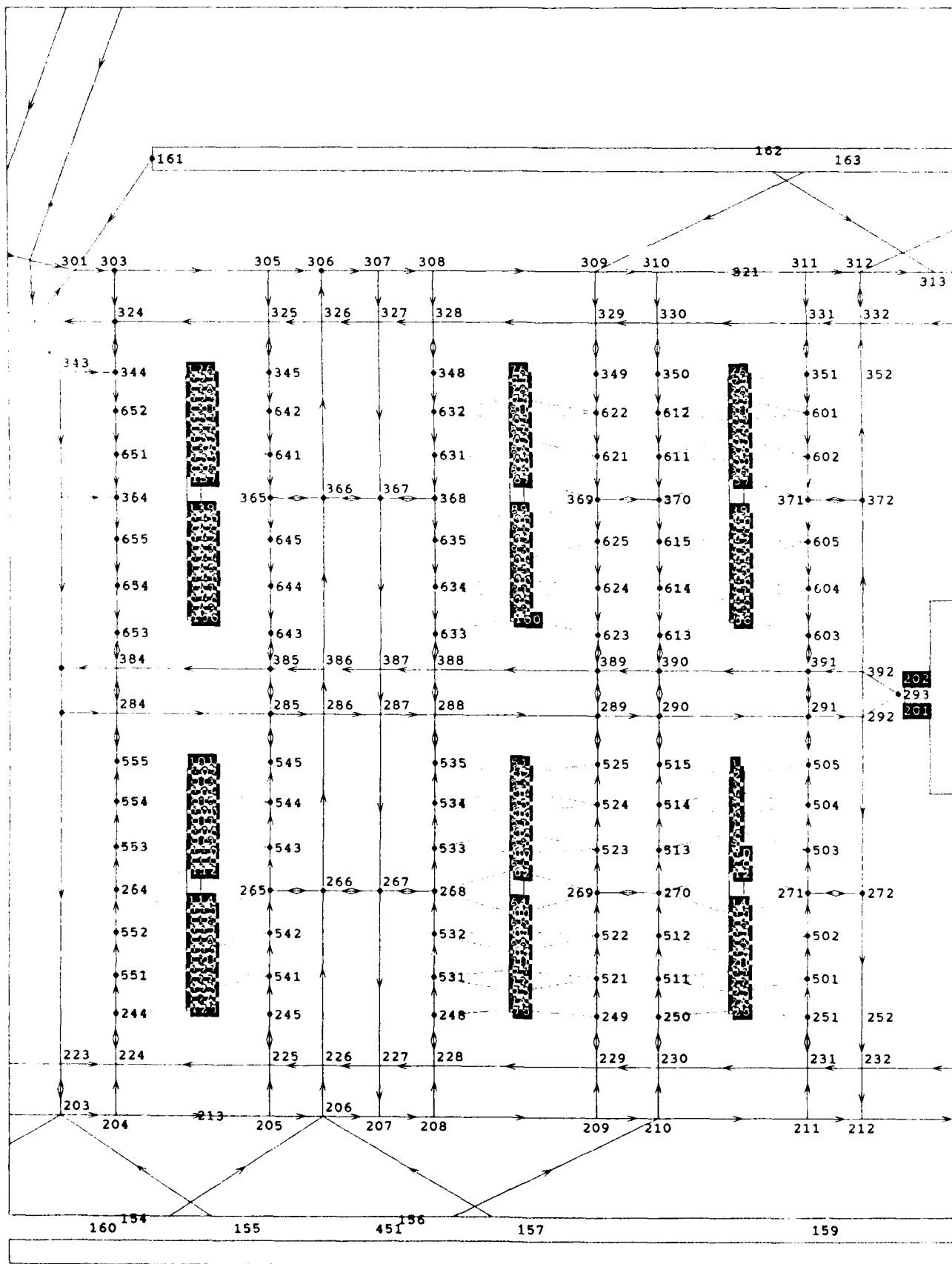Fig. C-32   IAD Gate Area